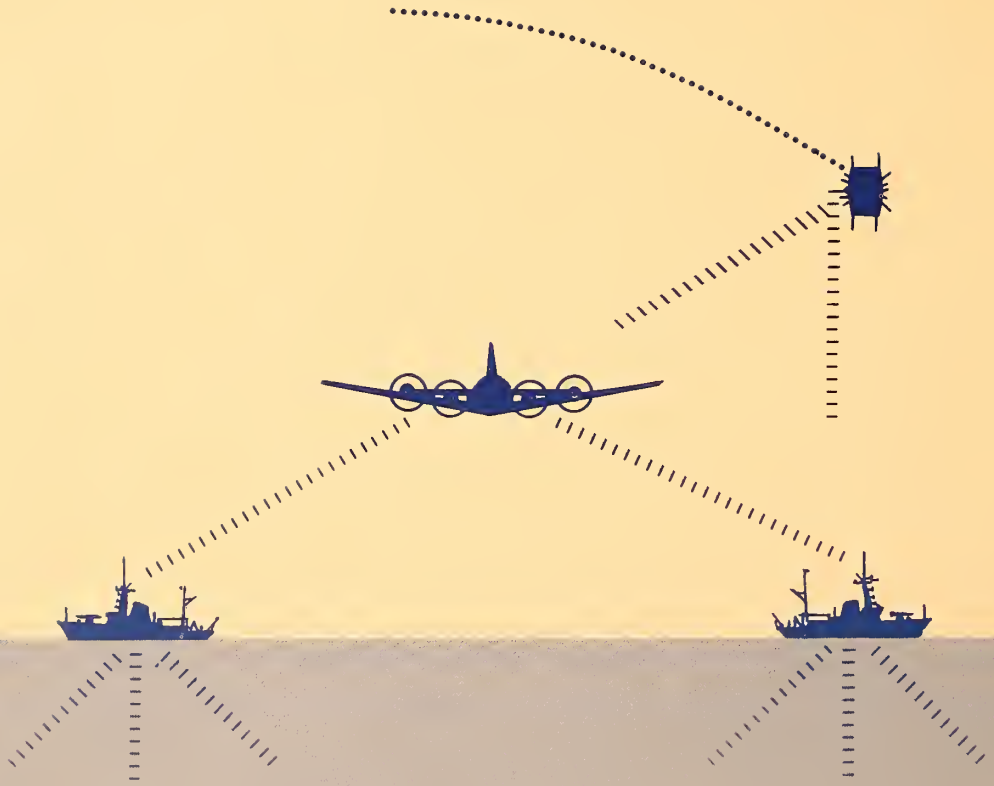
Proceedings of

FIRST MARINE GEODESY SYMPOSIUM

SEPTEMBER 28-30, 1966



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FIRST MARINE GEODESY SYMPOSIUM

COLUMBUS, OHIO

SEPTEMBER 28-30, 1966

Sponsored by Columbus Laboratories
BATTELLE MEMORIAL INSTITUTE

and Coast and Geodetic Survey
Environmental Science Services Administration
U.S. DEPARTMENT OF COMMERCE

The proceedings of the First Marine Geodesy Symposium are published by the U.S. Environmental Science Services Administration in the interest of fulfilling its statutory functions to provide information of interest and benefit to the scientific and engineering community. The opinions, views, and conclusions expressed in the papers and panel discussions reflect the interpretations of the authors and individual participants and do not necessarily represent the viewpoints of the Environmental Science Services Administration or other organizations participating in the Symposium. Inclusion of names and descriptions of products in this publication does not constitute an endorsement by the Environmental Science Services Administration.

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Foreword

FIRST MARINE GEODESY SYMPOSIUM

The theme of the First Marine Geodesy Symposium was "Marine Geodesy—Present and Future" with the following subdivisions:

(1) Marine Geodesy—The Problems
(2) Marine Geodesy—The Technologies
(3) Marine Geodesy—The Motivation

During the first day, the discussion was devoted to background material—geodetic principles and theories leading to the concept of marine geodesy and the interrelationship of marine geodesy and other scientific and technical fields. Various problems facing marine geodesists in the world ocean were discussed such as the implications of national and international laws concerning boundaries and the rights of ownership. Problems were examined in the light of government, industry, and scientific research requirements in both the continental shelves and deep waters. Particular attention was given to new problems such as the establishment of a worldwide datum for determining mean sea levels. The need for ocean gravity base stations to control surface-ship and air gravity measurements over the oceans was also discussed.

On the second, and part of the third day, techniques and methods that are employed in land geodesy and which could be used for marine geodesy were considered. The techniques involving underwater acoustics were described. The potential application of sound—the only form of energy that can propagate to considerable distances in the oceans—for absolute positioning, navigation, and marine geodesy was assessed. The application of fuel cells, conventional batteries, thermoelectric nuclear, and isotope power sources for ocean-floor systems was reviewed in terms of costs, life expectancy, and reliability.

Control points, distance and angle measurements, and accuracy of measurements were discussed with respect to surface, airborne, and satellite-based systems. The status of present systems and the outlook for possible future systems were covered in each case. Marine gravity-measuring instruments in underwater, surface-ship, and airborne systems were considered with respect to current status and role in determining deflection of the vertical and the shape of the geoid.

During the third day, satellite geodetic principles and techniques were discussed with respect to their use in the establishment of the World Geodetic System (WGS) and perhaps in the extension of this WGS to include the oceans. Also discussed was the application of satellite measurements to the establishment at sea of marine geodetic control and its use in precise navigation.

Next, the motivations behind marine geodesy—exploration, mapping, and exploitation of the world ocean—were examined as they relate to economics, defense, industry, and science.

Finally, the theme of the Symposium was projected into the future and anticipated challenges were highlighted.

One of the goals of this Symposium was to bring together representatives of the several disciplines involved in marine geodesy. Another aim was to broaden the source of geodetic talent, which has for some time been heavily concentrated in government and academic circles. Advancement of geodesy, and particularly marine geodesy, requires industrial know-how and capabilities in electronics, acoustics, and oceanographic instrumentation and systems. Moreover, international cooperation is essential if significant progress is to be made in marine geodesy.

It is hoped that this Symposium has served as a catalyst for geodetic cooperation among the various disciplines and technologies, the many interested scientists, engineers, and industrialists, and all the governments of the world. If talents are combined and efficient methods of working together are devised, the much-needed World Geodetic System and broad network of marine control points should be an achievement of the near future.

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Contents

	Page
Foreword	iii
Program Committee	iv
Greetings to Participants Vice President Hubert H. Humphrey	viii
Welcome by Battelle Memorial Institute B. D. Thomas	1
Welcome by U. S. Coast and Geodetic Survey Rear Admiral James C. Tison, Jr.	2
Summary of Vening Meinesz's Life W. A. Heiskanen	4

Marine Geodesy—The Problems

Session I: H. Moritz, *Chairman*

Purpose of the Symposium. W. A. Heiskanen	5
Background on Geodetic Principles and Theories P. D. Thomas	9
The Concept of Marine Geodesy A. G. Mourad	27
Relationship between Marine Geodesy and Oceanographic Measurements W. S. von Arx	37
The Law and Marine Geodesy W. T. Burke	43
Session I Panel Discussion	49

Session II: Capt. V. Moitoret, *Chairman*

Requirements and Views of DOD in Marine Geodesy Cdr. M. Macomber	51
Marine Geodetic Problems of Industry and Commerce K. E. Burg	55
Apollo Ship Navigation Accuracies and Requirements for Marine Geodesy S. S. Byrd	61
Plans and Programs of the U. S. Coast and Geodetic Survey Capt. D. Jones	65
Role of Marine Geodesy in the Scientific and Academic Community H. Moritz	69
A World Mean Sea Level and Marine Geodesy I. Hela and E. Lisitzin	71
Significance of Open-Ocean Gravity Base Stations and Calibration Lines L. Kivioja	75
Session II Panel Discussion	77

Marine Geodesy—The Technologies

Session III: A. G. Bogosian, *Chairman*

	Page
Underwater Acoustic Positioning: Principles and Problems W. A. Tyrrell	83
Underwater Acoustic Positioning: Applications F. N. Spiess	93
Underwater Power Sources for Marine Geodesy W. Kortier, M. Pobereskin, J. McCallum, and J. Gates	103
Shore-Based Electronic Systems for Marine Geodesy T. Hickley, A. Ferrara, and R. Ross	109
Application of Hyperbolic Radio Systems to Marine Geodesy W. N. Dean	115
Airborne DME Systems for Marine Geodesy Lt. Col. W. M. Robson	125
Acoustic Navigation: Surface and Subsurface J. B. Cline	135
Session III Panel Discussion	147

Session IV: C. A. Whitten, *Chairman*

Absolute Position Determination of Sonar Beacons H. E. Engel, D. E. Lev, A. Gelb	151
Geodetic Methods Applied to Acoustic Positioning A. C. Campbell	165
Precise Positioning With a Laser Theodolite L. Cunningham	171
Marine Gravity Surveying Instruments and Practice H. Orlin	181
Report on Prototype Gravity Measuring System, Constructed by Bell Aerosystems Company for U.S. Naval Oceanographic Office and U.S. Coast and Geodetic Survey Prepared by Gravity Division, USNOO	189
A New Ocean-Floor Gravimeter Utilizing a Vibrating String Accelerometer R. O. Bock and C. Wing	195
Ocean Gravity Surveys With Airborne Systems B. Szabo	201
Identification of Deflection of the Vertical Using an Inertial System C. L. Bradley, H. J. Sandberg, and J. DeMatteo	205
Underwater Gravity Measurement in the Baltic Sea and in the Barents Sea T. Honkasalo	217
Session IV Panel Discussion	221

Session V: R. R. Newton, *Chairman*

The Navy Navigation Satellite System R. R. Newton	224
Experiences With U.S. Navy's Navigation Satellite System M. Talwani	225
Secor Satellite Ranging System and Its Application to Marine Geodesy K. Rinner	229
Photogrammetric Ocean Survey Equipment H. Jury	239
Session V Panel Discussion	247

Marine Geodesy—The Motivations

Session VI: R. A. Geyer, *Chairman*

	Page
Activities and Developments in the U.S. Continental Shelf Regions--Motivations for Marine Geodesy N. A. Frazier and F. H. Buttner	249
Bathymetric Maps for Continental Shelf Development Capt. L. G. Taylor	255
The Economic Motivation--Geology and Geophysics for Oil and Mineral Exploration L. L. Nettleton	261
Deep Submergence: Its Technical and Geodetic Implications Lt. Cdr. M. MacKinnon and A. J. Coyle	269
Session VI Panel Discussion	275
Special Panel Discussion	279
Closing Address: Where Do We Go From Here? G. P. Woollard	283
List of Participants	287

Greetings to Participants

Please convey my greetings to the distinguished participants and audience at the First Marine Geodesy Symposium being held at the Battelle Memorial Institute. Your conference is a commendable example of initiative by forward-looking scientists and engineers who recognize that both our domestic and international activities in the ocean require precise navigation and location systems. As chairman of the National Council on Marine Resources and Engineering Development, I am deeply gratified by these efforts. This nation is committed to the expansion of scientific knowledge about the marine environment. We are also committed to the accelerated development of marine resources. To this end we welcome international participation in order that the potential of the sea can be used for the benefit of all men.

My best wishes for a successful and fruitful meeting.

Hubert H. Humphrey
Vice President
United States of America

Welcome by Battelle Memorial Institute

B. D. Thomas, *President*

Ladies and gentlemen, it is my present duty and privilege to extend to you the official welcome of the Battelle Memorial Institute to this first Marine Geodesy Symposium. This is a very significant meeting. I am told it is one of the largest groups of geodesists ever to get together. Furthermore, it appears to be the first meeting devoted to marine geodesy. It seems strange in a way that we should have waited so long. After all the manifest significance of the sea in geodesy seems so obvious that it is strange that it has been neglected. Now it appears that we are going to make up for our neglect.

I say somewhat apologetically that I am a chemist by training. I have been in administrative work so long that chemistry is only a sort of a receding memory. Now, on many occasions when I introduce or welcome symposia of this sort, I always have to stifle an impulse to jump into the program and try to be a scientist, which I know I am not—to reassert some nostalgic claim that probably goes back to the days of my childhood or something like that. Usually, I resist this, but today I cannot. First of all I would like to qualify myself a little bit. There was a time, a long time ago, actually, when I hooked a bunch of Nansen bottles on to a cable, lowered them about a mile down into the North Pacific, raised them up and took the samples of the water, recorded the temperature, determined the salinity, or in those days "chlorinity," and with the aid of a desk calculator worked out the isodensity lines, calculated the Coriolis forces and from that reduced the velocity of the current. This much I remember, but the rest of it is kind of hazy. Let me say it was very educational. The thing that I remember the most out of this is the sea itself. For one who has grown up on the sea coast, coming to the mid-continent and staying as I have for some 32 years, is still something of an exile--the sea runs in my veins. The only reason I tell you this is I wanted some essence to what I say, that this symposium is significant and that I know something of what I am talking about.

I think a lot of the unsolved problems in geosciences, generally, are going to come from the attack that you are now making on marine geodesy. I have long had a pet theory that the sea, the land, and the polar ice cap constitute a relaxation oscillator that gives a lot of counts--perhaps even for the ice age--most of the tectonic forces that the geologists are still trying to explain. I have never been able to put this theory into a sufficiently respectable form to advance it formally. I have the feeling that this matter, the power of the sea and its consistent warfare with the land is maybe the most important thing that is going on in the world of geosciences and it is high time that we were getting at it.

Now, of course, you who are present at this meeting are going about this with the steady sureness of science and the scientific methods. In a way you are entering relatively unexplored areas, but I think you should feel that there are going to be fruitful results which are going to extend into geology, chemistry, physics, biology, meteorology and more of the sciences. But more than that, and I cannot say more significantly, because this is a matter of human values, that this work is likely to have tremendous practical importance in the field of economics, sociology, maybe even in politics, and if you can do a good job in political science today the world will certainly live to thank you.

I express again our welcome on behalf of Battelle. I wish you the best of success for this meeting and I hope there will be some continuation. Thank you.

Welcome by U.S. Coast and Geodetic Survey

Rear Admiral J. C. Tison, Jr., *Director*

For many years, the Coast and Geodetic Survey has enjoyed a pleasant and cordial relationship with the Battelle Memorial Institute. I want to take this opportunity to thank Dr. Thomas for this friendly spirit of cooperation, and express my personal appreciation for the hospitality extended by Battelle to all of us here in Columbus.

The Coast and Geodetic Survey is keenly interested in the development of precise geodetic techniques for use beyond the limits of the continents as another step toward man's maximum utilization of our planet's resources. We have been looking forward enthusiastically to this First Marine Geodesy Symposium for which it is our privilege to be cosponsor with the Battelle Memorial Institute.

I think it is appropriate to restate the words of President Johnson--which he used a little more than a year ago--when he described the Environmental Science Services Administration as "a single national focus to describe, understand, and predict the state of the oceans, the state of the upper and lower atmosphere, and the size and shape of the earth." This concept is not new, but the present interest in the effective use of the sea has brought out the significance of our work.

This is particularly true of the continental shelves and slopes surrounding the continental margins of the United States which are now being brought into more critical focus. These continental margins have attracted more interest and resulted in more discussion to date than any other submarine area. Accelerated surveying operations in these areas are necessary for exploitation to be undertaken, in due time, of undiscovered natural resources. Recognizing that economic growth depends upon natural resources, ESSA will expand and enlarge its programs toward greater contributions in the development of a natural marine resources program for the future.

Science and technology of the oceans have now reached a new plateau from which we may view and plan for the next phase. Planning for the future demands dedication, an intense attitude toward responsibility and a realization of our mission as individuals and our agency responsibilities.

The initial stage of a Federally-supported national ocean program is predicated on intensive research in all aspects of marine science. Specialized institutions are enlarging their staffs of scientists and technicians with plans to train more research workers. New professorships are being created, research ships are being built and commissioned, and industry is constantly devising new instruments of exploration. All this eager progress will have to be maintained for years if oceanography is to render the benefits expected of it.

The increasing activity of research workers is directed either towards problems already under study or new objectives conducive to significant discoveries. Among the phenomena on which light has recently been shed in the field of physical oceanography are the meanderings of the Gulf Stream, as evidenced by the work of the USC&GS ship *Explorer* during the past several seasons.

Geodesy is one of the oldest of the sciences. Some scientists in other branches of geophysics have remarked that there is little left for the geodesists to do--but we know this is not the case. Geodesy involves the frontiers of exploration of all facets of our earth and the space around us and is one of the most precise of any of the sciences. Our mission for establishing geodetic control on the earth's land surface is far from complete; now our expanding civilization requires that we look beyond our continents to the exploration and development of the marine environment. Any orderly plan for the exploitation of marine resources must recognize fundamental geodetic requirements as an essential part. You who are associated with any phase of this total program are fully aware of the challenges and opportunities before us.

Marine geodesy is especially applicable in the unique situation existing in the Gulf of Mexico. It is necessary that mineral leases, and the structures for the extraction of minerals from the seabed of the Gulf, be adequately positioned in reference to the coastline and in reference to other structures that now exist or will be established in the future. This requires a system of geodetic control similar to that used on land.

Much has been done to meet this problem in the Gulf and activities in the region point up what will be needed in other continental shelf areas.

In the late 1950s, a committee, representing companies interested in oil development in the Gulf of Mexico proposed that basic geodetic control be strengthened along the coastline and extended into the Gulf for location of oil platforms. This committee representing the interested companies proposed that the Coast and Geodetic Survey establish this control on a cooperative basis. This was done, and the work was further extended in the mid-1960s under similar arrangement. The scheme of triangulation in the Gulf coast region has been strengthened and densified with offshore extensions for an average distance of about 60 miles. The technique thus evolved will be enlarged and applied to other areas as ESSA's marine geodesy program moves ahead.

We must continue our efforts to understand the total environment in which we live. Only through complete understanding can we utilize and provide some measures of control over our environment. We are now dealing with our last great frontier. The challenge that we must accept is of immense proportions, involving as it does the vast submerged and invisible regions of our globe. Before economic benefits can be realized, the ocean floor treasures must be located, sampled, and cataloged. The first task to be pursued and mastered is the extension of geodetic control into the offshore region. This symposium will contribute greatly to our immediate progress in the initial phase of our National Oceanographic Program.

The Coast and Geodetic Survey joins with Battelle Memorial Institute in welcoming you to this First Marine Geodesy Symposium. During the coming days you will find opportunities to discuss and debate some of the basic problems, to become more informed about the latest technology, and to be stimulated by the urgency and responsibility associated with this expanding application of the scientific and engineering aspects of geodesy carried out in the environment of the oceans.

I wish you success in all of your deliberations.

Summary of Vening Meinesz's Life

W. A. Heiskanen

Isostatic Institute
Helsinki, Finland

I am indeed very grateful to Dr. B. D. Thomas, President of Battelle Memorial Institute and to Rear Admiral J. C. Tison, Director of U.S. Coast and Geodetic Survey, who have made this important symposium possible. I also thank Dr. A. G. Mourad, energetic and talented leader of our symposium, and Professor Helmut Moritz, President of the German Geodetic Commission, for his nice words.

Before my address I would like to deliver a short obituary of a most famous geodesist and geophysicist of this century, Professor F. A. Vening Meinesz, who passed away August 11, 1966, at 80 years and 12 days. This was a very large loss for several sciences, particularly geodesy and geophysics, because Professor Vening Meinesz with his pendulum apparatus gravity observations at sea opened a new era for the gravimetric method and physical geodesy.

F. A. Vening Meinesz was educated in Amsterdam and at the Technical University of Delft. He made a gravity survey of the Netherlands (1911-1920). After he had developed a method for making accurate pendulum observations on the mobile ground in the western and northern parts of this country, he applied this method to the problem of accurate gravity observations at sea. He made eleven submarine expeditions (1923-1938), covering more than 120,000 miles.

Dr. Vening Meinesz was Professor of Geodesy and Geophysics at the University of Utrecht (1927-1957) and Professor of Physical Geodesy at the Technical University of Delft (1938-1957).

Vening Meinesz published 12 books and innumerable smaller articles dealing with his pendulum apparatus, results of his submarine expeditions, and gravimetric interpretations.

He was an honorary member of 30 Academies of Sciences and other learned associations and honorary doctor of 10 universities. The following medals were bestowed on him: the Plancius Medal (Royal Netherlands Geographical Society, 1930), the Howard N. Potts Medal (Franklin Institute, Philadelphia, 1936), the Penrose Medal (Geological Society of America, 1945), the William Bowie Medal (American Geophysical Union, 1947), the Alexander Agassiz Medal (U.S. National Academy of Sciences, 1947), the Waterschoot van der Gracht Medal (Royal Netherlands Geological and Mining Society, 1951), the Leopold von Buch Medal (German Geological Society, 1959), and the Wollaston Medal (Geological Society of London, 1962). In 1962, Dr. Vening Meinesz received the Vetlesen Prize.

The passing of Professor Vening Meinesz was particularly sad to me, because we had been the best of friends since 1927, when we met for the first time in Prague at the General Assembly of the International Union of Geodesy and Geophysics (IUGG). We both worked along similar lines. We worked enthusiastically with isostasy, physical geodesy, and the structure of the earth's crust. If we were, rather seldom, of different opinion, the conversations were always constructive.

I consider it a great honor to be co-author with Prof. Vening Meinesz of the textbook *Earth and its Gravity Field*. His last book was *The Earth's Crust and Mantle*, published in 1964.

Our geodesy friends, however, at the Lisbon General Assembly of the IUGG, in 1933, were not quite satisfied, because they joked: "Why haven't you, Vening Meinesz, suggested that Heiskanen, who is 38 cm smaller than you, carry out observations in the small submarines and why haven't you carried out on the dry land studies concerning isostasy and the structure of the earth's crust?"

Only in my older years have I learned entirely to grasp what a gift of God it has been for me to have had such a colleague, friend, and brother in Christ as Professor Vening Meinesz.

Prof. Vening Meinesz was Finland's keen friend. He visited Finland five times. He was a member of Finnish Academy of Sciences, 1941, and Honorary Doctor of Finland's Technical University, 1949. As President of the IUGG, he was instrumental in having the Isostatic Institute of the IAG (International Association of Geodesy) established in Helsinki, in 1936.

Purpose of the Symposium

W. A. Heiskanen

Isostatic Institute
Helsinki, Finland

The First Symposium of Marine Geodesy was established, because the oceans, 70 percent of the earth surface, are geodetically and gravimetrically unsurveyed. In this revolutionary age of navigation, aviation, rockets, artificial satellites and conquering of universe, geodesy has to solve many important and difficult problems. Solutions will be found if not only the continents but also the oceans, at the surface and the bottom, are surveyed. This is the task of marine geodesy.

Like land-based geodesy, marine geodesy has to use the methods of physical geodesy and consider isostasy. The Airy-Heiskanen isostatic system

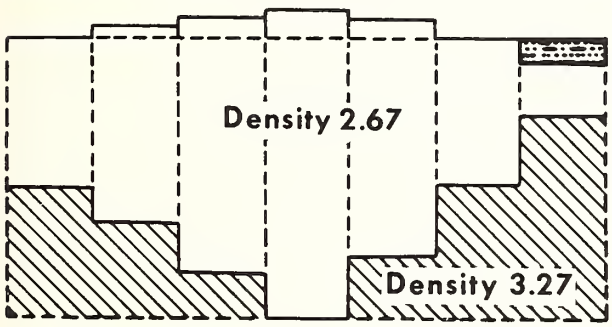

FIGURE 1.—Airy-Heiskanen isostatic system.

is illustrated in figure 1. This system is much used in geophysics and physical geodesy. The obtained values of the thickness of the earth's crust are in agreement with the results of other methods.

In his Ph.D. dissertation in 1924, and later on with his students, Heiskanen computed isostatic reduction tables, and with his students used his modified theory to determine the thickness of the earth's crust in the Alps, the Caucasus, Norway, the Rocky Mountains, the Ferghana Basin, and the Carpathians. For these studies they collected in Helsinki enough gravimetric material, including the measurements made by Vening Meinesz at sea by submarine 1923-1930, so that in 1931 Heiskanen and his students were able to start on the first gravimetric computation of the shape of the geoid. Their first publication on the gravimetric geoid (by R. A. Hirvonen) appeared in 1934; the second geoid (that of L. Tanni), based on a larger gravity sample, appeared in 1948. Of the more recent geoids, three are mentioned in chronological order: The Zhongholovish geoid, 1952, Eastern hemisphere; the Geoid of Europe, part of Columbus geoid, Heiskanen, 1957; and the Gravity and Satellite geoid according to Uotila, 1962.

My dream to establish physical geodesy on a worldwide scale, based on gravity measurements and gravity anomalies, was born in the 1930s and materialized in the fall of 1950, at the Conference of the Mapping and Charting Research Laboratory of the Ohio State University, arranged by the laboratory's Director, Professor George H. Harding, in collaboration with his staff. At that time I had an opportunity to present my ideas. They were published under the title *On the World Geodetic System*, Publication No. 1, Institute of Geodesy, Photogrammetry, and Cartography, Ohio State University, Columbus, Ohio, 1951, and later on, also in other scientific series.

Principles and Prerequisites of Physical Geodesy

The principles of physical geodesy are very simple. It needs only one quantity, the gravity anomaly Δg, because the real irregularities of the geoid, i. e., the quantities N, ξ, and η, and the gravity anomalies Δg result from the same cause; namely, from the visible or invisible existing mass irregularities Δm of the earth. The gravity anomalies Δg can be obtained from observed gravity values and the quantities N, ξ, and η can be computed on the basis of these gravity anomalies. The Stokes' theorem of 1849 permits us to compute the N-values; the derivatives of it, by the F. A. Vening Meinesz formula of 1928, will yield the quantities ξ and η.

The quantity Δg is very small. The ratio $\Delta g/g$ is only 10^{-6} cm sec^{-2}. Also modern gravimeters are small and accurate. Worden's gravimeter

weighs only 3 kg. Gravity observations take only 3-5 minutes and yield an accuracy of 0.2 mgal.

The following prerequisites must exist:

1. All gravity observations must be converted to the same world gravimetric system. This was accomplished by R. A. Hirvonen in 1948 and by U. A. Uotila in 1963, using all available gravity base stations at those times.

2. A suitable gravity formula must be used. The geodetic and gravimetric parameters a = 6378140 m; f = 1: 298.3; γ_E = 978040 mgal; B = 0.0053009; and ϵ = 0.0000059 appear to be acceptable values.

3. Existing g and Δg data must be entered on punch cards; Uotila had already used punch cards and computer by 1957.

4. All existing gravity material must be available to the geodetic institutions and individual scientists. The negative attitude of some groups makes this impossible.

5. All gravity anomalies Δg must be as accurate and representative as possible; the isostatic reduction of Δg (Airy-Heiskanen system) is best and most representative.

6. There must be a tight gravity net around the computation points and a reasonable knowledge of the Δg's around the world.

If this is done, all important geodetic problems except the most important one, quantity a, the radius of the equator of the reference ellipsoid, can be determined. This parameter is obtained from astrogeodetic arc measurements. The measurements by all countries should be such that the same calibrated length unit has been used for the field base lines. This length unit can be obtained from the standard base lines measured by Y. Vaisala's light interference comparator which yields a relative accuracy of 1:10,000,000.

The radius a also is the fundamental astronomical constant, because it is used to determine the radius of the sun, the distances between the planets and stars, and even the dimension of the universe.

How far have we come in the gravimetric exploration of the oceans? The efforts of Vening Meinesz, L. Worzel, C. Morelli, G. J. Bruins, B. C. Browne, P. Dehlinger, J. C. Harrison, A. C. Hamilton, Hyman Orlin, and others, have contributed much to the measurement of gravity at sea, nevertheless, there still are huge gaps in the gravity anomaly field, according to a paper by U. A. Uotila, "Existing Surface Gravity Material," published in *Gravity Anomalies: Unsurveyed Areas*, Geophysical Monograph No. 9, American Geophysical Union, Washington, D.C. 1966. The total coverage for the entire earth is now about 35 percent. However, the distribution is extremely poor--the largest gap being in the South Pacific Ocean. These very large unsurveyed areas degrade our computational results because, as we well know, the gravity anomalies are correlated with each other. Therefore, the large unsurveyed areas might have a serious systematic effect.

The extent of published material will be evident from the listing of 858 publications which will be available at a later date and which will include about 150,000 stations for which gravity information is given.

Main Problem of Physical Geodesy and Marine Geodesy

The key problem of physical geodesy is how to fill the gaps. There are three methods: (1) We can make additional measurements, particularly in ocean areas; (2) we can extrapolate from the existing gravity anomalies, obtaining mean gravity anomalies for the unsurveyed areas by statistical methods; or (3) we can use geophysical methods. But until the gravity anomaly gaps are filled by additional measurements, we must employ the statistical and geophysical methods, otherwise research in physical geodesy will come to a standstill.

Gravimetric Survey Methods in Ocean Areas

Methods used to obtain gravity measurements at sea include:

1. Measurements made from submarines (Vening Meinesz); little used today.

2. Measurements made at sea level (shipborne surveys); accuracy not yet sufficient.

3. Measurements made from airplanes (airborne surveys); accuracy not yet sufficient.

4. Measurements made on the ocean bottom; reliable only in shallow waters along the ocean shorelines (7 percent of oceanic area), but the method is good.

Therefore, at present, we must rely upon the statistical and geophysical methods.

The statistical method is very useful and important and has been applied for many years. If the gaps of the gravity anomaly field are small, say, 1,000-1,000,000 km^2, the different modifications of the statistical method would predict sufficiently good point values and mean gravity anomaly values. The studies of Hirvonen, Moritz, Uotila, Rapp, Tengstrom, Tsuboi, Lambert, and Kivioja in Columbus, and of several of our western and eastern colleagues, indicate rapid progress in the development of this method. The statistical method, however, cannot be used to predict gravity anomalies over long distances or for large areas.

The geophysical method is based on the fact that about 90 percent of the topographic masses of the lands and the oceans will be compensated by the isostatic compensation, except in several local areas where isostatic compensation is not

complete. Thus, we can claim that the topographic and compensating masses will produce about 90 percent of the gravity anomalies.

In 1962, Uotila computed the mean elevations of 5° x 5° squares from the development of the topography in spherical harmonics and used no observed gravity anomalies in computing the mean anomalies, whereas Kivioja, in 1963, estimated the mean elevations from topographic and bathymetric maps and adjusted the obtained mean anomalies of the unsurveyed areas on the basis of the known mean anomalies. Therefore, their results cannot be the same, although the differences are, in general, rather small.

The results will certainly improve when the mean elevations of 1° x 1° blocks are available. When the gaps of the gravity anomaly field are filled by new accurate observations, we can compare the predicted Δg_m values of Uotila and Kivioja with the true mean anomalies.

I am very interested in the geophysical method. When the correlation between the geological phenomena and gravity anomalies is better studied, the accuracy of the obtained mean anomalies of 1° x 1° blocks will increase.

Illustration of Present Geodesy

We have seen that only 35 percent of the world has been covered by a thin gravity station net, where at least the mean gravity anomaly of 1° x 1° block exists. Only about 5 percent of this total has been measured over shallow shelf areas. Geodesy's achievement can be compared with a man who has one strong but thin leg on land, while his ocean leg is thick but paralyzed and unable to function. The thin leg on land is not sufficient for the man who would work. To do work, it is required to have two strong legs--one on the land, one in the oceans.

A Look at the Future

The most important problems of the future are the following:

1. We must establish in the oceans a grid of geodetic and gravimetric reference points.

2. The reference points must be established at the floor of the ocean, and not at the ocean surface, or at any depth between surface and floor. A long-lasting power source may solve the problem of ocean floor geodetic and gravimetric reference points.

3. The grid must be connected to the world geodetic and gravimetric systems of the continents.

4. "Horizontal photographing" of the ocean bottom is our next goal. In fact "topographic maps" of 200 meters radius are already possible at 500 meters depth.

5. The oceans must be covered by sufficiently accurate maps. The problems are the most difficult that geodesists have ever had.

These problems are only brain and money problems. It is more fascinating and inspiring to try to solve difficult problems than easy ones. I like the slogan: Easy problems will be solved today, difficult ones tomorrow, and the impossible problems the day after tomorrow. One hardly can find problems which cannot be solved if they really are worthwhile solving. For instance, during the last two decades, the problems of radar, the atom bomb, artificial satellite flight to the moon, exploring Mars, and so on, which also were very difficult, have been solved.

From the point of view of mankind, the problems of marine geodesy are very important. It will mean much for geodesy, geophysics, oil and mineral exploration, seismology, navigation, and aviation when the oceans are covered by adequate maps and a grid of geodetic and gravimetric reference points is established on the ocean floor.

We know that the continents cover about 30 percent of the earth's surface and the oceans over 70 percent of it. In addition, we know that only 35 percent of the continent area is surveyed gravimetrically, and only about 15 percent of the ocean area. On the other hand, we know that physical geodesy can solve the important geodetic problems only when a relatively uniform gravity net covers the whole earth's surface.

I am sure that all geodesists would like to solve the main geodetic problems as soon as possible. This can best be accomplished by physical geodesists supporting a program to fill the big gaps in the gravity field. We must also remember that "best" is the enemy of "good." The mathematical technique is already so advanced that the present accuracy of the computed quantities can hardly increase without additional data. But, if we fill the big gaps, the results should improve dramatically.

Seven years ago, I finished my address at the annual meeting of the American Geophysical Union something like this: "During the war between Rome and Carthage, the patriot consul Cato finished all his addresses with the classic words *ceterum censeo Charthaginem esse delendum* (Carthage must be destroyed)." I would like to say that the problems of physical and marine geodesy can be solved fast and relatively well as soon as the big gaps in the gravity field are destroyed.

I have been 7 years as geodesist at the Finnish Geodetic Institute, Helsinki; 22 years as professor of Geodesy at Finland's Institute of Technology; 30 years as Director of the Isostatic Institute of IAG, Helsinki; 24 years as dozent of astronomy at Helsinki University; 3 years as a member of Finland's Parliament; 12 years as director of the

Finnish Geodetic Institute; 15 years as professor of geodesy at the Ohio State University; and 13 years as establisher and leader of the Worldwide Geophysical Research Project—totaling 126 years. It is no wonder that I am already professor emeritus and prone to making errors.

I am indeed very happy, to be a small part of this great symposium, to meet hundreds of esteemed scientists and leaders and a legion of my former students and colleagues, and to listen to the lectures of the many speakers gathered here.

Background on Geodetic Principles and Theories

P. D. Thomas

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"In fact, it would seem that only those who had some first-hand experience in the acquisition of new knowledge in some disciplined field would be able truly to appreciate how great the science of the past has been, and would be able to measure these giant accomplishments against their own efforts to penetrate a few millimeters further into the darkness that surrounds them."—J. R. Oppenheimer.

Geodesy, one of the early emergent disciplines of the earth sciences, is indispensable in the practical aspects of relating to each other those parts of the lithosphere where man conducts most of his activities, that is the parts of the lithosphere protruding through the oceans. The problems of determining the form, size, internal structure, and gravity field have provided a basis for continuing study. The development has been colorful, both in techniques and equipment. Many mathematicians and other scientists through the years have contributed to its growth and have in turn been stimulated to greater creativity by the association. Their deductions have been remarkable considering the limited numbers of useful physical measurements available. The advent of artificial earth satellites and their use in both geometric and dynamic modes is providing the geodesist with the means of refining his ellipsoid models of the earth and in concert with other earth sciences is improving the concepts of the earth's internal structure. With the extension of geodetic control to the seas in support of international programs in oceanography and upper mantle studies, and ultimate refinement appears to be attainable.

Let us review briefly the commonly accepted *structure* of the earth, then the *figure* of the earth (its form and size), and in turn the support given by geodesy to the other earth sciences in studies such as the upper mantle project [Hart, 1964; Ringwood, 1962], through observations of associated phenomena such as crustal deformation or slippage, and earthquakes. Finally we will note the several ways that extending geodetic control to the seas will improve the geophysical investigations of the earth.

THE HYPOTHESIZED INTERNAL STRUCTURE

For scientific purposes there are four main structural divisions as shown in figure 1; the crust, the mantle, the liquid core, and the solid core. Note that the topographical features have been greatly exaggerated.

The *crust* is thought to be made up of at least two layers; a granite upper layer, a basaltic lower layer. It is believed that relatively light rocks extend to greater depths beneath continents than elsewhere and that mountains are held up by their roots. The crust may be as much as 30 km. thick beneath continents and 60 km. beneath mountains, with most of the thickening occurring in the basaltic layer. Under oceans the granite part of the crust is completely missing and there is a very thin basaltic crust between the mantle and the sediments that are being deposited in the ocean bottoms.

The *mantle* is believed to be made up of rocks that more appropriately belong to the ultrabasic range. That is they have *relatively little silica* and a higher proportion of iron and magnesium. As indicated in figure 1, earthquakes can occur down to a depth of about 650 km., that is the mantle is active down to that depth, and we have as *the upper mantle* that part which, being active, can influence conditions within the crust with its base the depth of the lowest earthquake. The earth's core is thought to be nickel-iron and its central part believed to be solid.

We actually know very little about the interior of the earth. We do not know if it is cooling down or heating up or whether it is contracting or expanding [Beck, 1961]. The question of contraction or expansion may be related to the possibility that the constant of gravitation is changing with time and may be actually unrelated to the

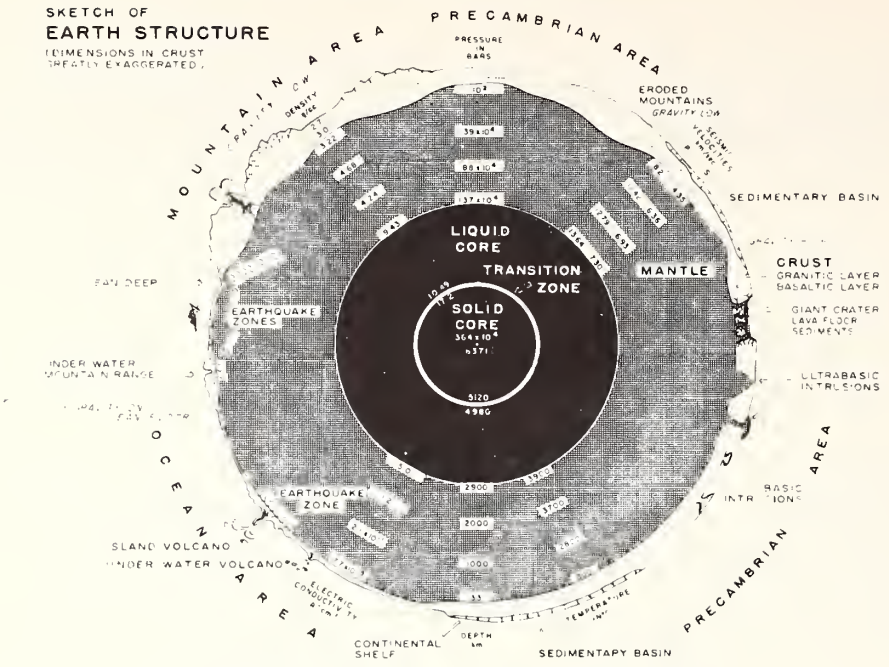


FIGURE 1.—Model of earth's structural divisions.

earth's internal temperature. Paleomagnetic studies indicate that the continents may be drifting. We are not very certain about the rock types that may be found in the crust and mantle. These are usually inferred from rocks that appear on the surface and by comparing the values of seismic velocities measured through earthquake waves with those measured in the laboratory for the various rock types. A worldwide discontinuity in the velocity of transmission of seismic waves is known to exist, the Mohorovičić discontinuity or *Moho*, which apparently forms the separation layer between the crust and the mantle. It is identified with that required by isostatic theory which hypothesizes that the height of the earth's surface at any place is a function of the average density of the underlying rock column. The nature of the compositional change at the Moho has not been determined [Howell et al, 1961], but in 1961 the first coring sample of oceanic basalt, off the coast of Mexico near Guadalupe Island (beneath 500 feet of soft sediment), was very low in potassium and slightly *over saturated with silica.* This variance with respect to theory has had its scientific reverberations and a day of truth for the scientific community awaits the results of the actual drilling of the mantle north of Maui, Hawaii, which hopefully will begin by late 1968 [Lill, 1961, 1965].

Very little is actually known about the genesis or mechanisms which produce the several manifestations of activity in the upper mantle, or lower strata of the earth's crust, such as upheavals and subsidences [Jardetzky, 1962], wrinkling of layers into folds [Beloussov, 1961], formation of fissures, earthquakes, formation of molten magma, volcanic eruptions, formation of magmatic intrusions.

THE FIGURE OF THE EARTH

Pythagoras and his school in the sixth century B.C. are usually given credit for the idea that the earth is spherical as perpetuated by the later Greek philosophers such as Plato and Aristotle. But it is hard to believe that neither the Babylonians nor Egyptians realized, with their profound interest in astronomy, that it was the earth's circular shadow which crept across the moon during lunar eclipses.

Eratosthenes, in the third century B.C., made the first measurement of the earth's circumference. He noted that the rays of the sun, vertical at Syene (modern Aswan), made an angle at Alexandria (almost due north) of 7.2 degrees with the vertical or 1/50 of a circle. The circumference of the earth was then 50 times the distance between Alexandria and Aswan. His result was remarkably good considering that he had to estimate the Alexandria-Aswan arc from the time it took a camel to make the trip and the distance a camel could travel in a day. His method is still essentially (arc measurement plus celestial observations) a principal technique.

Snell, better known for the sine law of refraction, published in 1617 a determination of the length of the meridional degree as obtained from a triangulation in North Holland. Picard's triangulation in France, begun in 1669, used for the first time in geodetic surveying, a quadrant

graduated in minutes and seconds, mounting telescopes whose oculars had crosshairs for sighting instead of the usual pin-hole alidades. Richer, who in 1672 led a French expedition to Cayenne (French Guiana, South America) obtained the first indication that the earth might be flattened at the poles. A pendulum clock, which kept good time at Paris, lost 2 1/2 minutes at Cayenne. Since Newton's law of gravitation was yet to be published, no numerical values could be obtained.

Newton made the first theoretical estimate of the flattening as found in his *Principia, 1687*. His argument was essentially the following: Imagine a tube or canal of water running from the north pole to the center of the earth and another from the center to a point on the equator as shown in figure 2. Since water shows no tendency to run

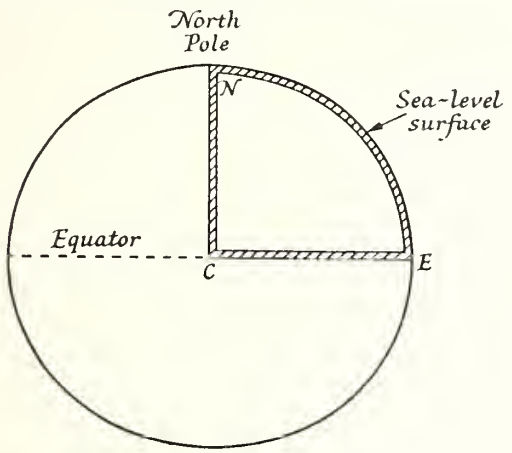


FIGURE 2.—Newton's argument for the Earth's flattening—by balancing polar, CN, and equatorial, CE, canals of water.

from equator to pole or from pole to the equator over the surface, the pressure exerted by each canal at the center of the earth must be equal. But because of the earth's rotation, gravity is slightly less in the equatorial canal, which will therefore be longer [King-Hele, 1964]. Although Newton's estimate of 1/230 for the flattening was too large (he had not allowed for increasing density toward the center of the earth) it remained the best and most soundly based estimate for nearly a century.

The mathematician J. D. Cassini and his son deduced a negative value for the flattening from arc measurements in northern and southern France. Their value, -1/95, published in 1720, implied that the earth was elongated at the poles like a football. It precipitated a controversy which was finally settled by expeditions of the French Academy of Science sent to Lapland and Peru to measure arcs of the earth's meridian. Their measurements finished in 1737 and 1743, respectively, showed that the length of the degree was greater in Lapland than in Peru or Paris and confirmed Newton's results. The metric system, proposed by the French, defined the meter as 1/10,000,000 part of the earth's meridional quadrant. Scale was determined from an arc of triangulation completed between Dunkirk and Barcelona in 1791. Thus perfection of theodolites, precision levels, and base line measuring apparatus, made possible the establishing of conventional triangulation and level nets on the several continents and island chains. Sea barriers effectively prevented interconnection of most of them until more recent times. Pendulum gravity measurements were being made and Clairaut, the French mathematician who had been a member of the Lapland expedition, developed in 1743 the theoretical basis for studying the form of the earth from gravity measurements which has subsequently needed only minor amendments (Clairaut gave a first order development. Many second order developments have since appeared, that of de Sitter's in 1924 being perhaps the most convenient.)

Since geodetic field instruments have level bubbles and elevations are referred to mean sea level, the proper *geodetic figure of the earth is the geoid*, a level surface or *equipotential surface* (everywhere orthogonal to the direction of gravity) approximately coincident with the sea level surface, and approximately an ellipsoid of revolution with its minor axis coincident with the rotational axis of the earth. Since topography and varying crustal densities affect the shape of the geoid, particularly under the mountains, it is not smooth but has warpings and other irregularities. The geoid, a physical reality, is the surface which the geodesist approximates with a smooth spheroid or ellipsoid of revolution of best fit.

The computation on the ellipsoid of geodetic lines, or geodesics, which connect the stations in triangulations or traverse, is not trival. A triangulation station, P, on the lithosphere is assumed to be the foot, P', of the perpendicular from P on the ellipsoid as shown in figure 3. Normals from P to the two surfaces as shown make an angle with each other called a deviation of the vertical and there may be such a deviation for each station of the net. The projection of the geoid normal upon the meridian gives the meridional component of the deviation which is then the difference of the astronomic and geodetic latitudes. Analogously the component in the prime vertical (the plane normal to the meridian containing the perpendicular to the ellipsoid) is the difference of the astronomic and geodetic longitudes multiplied by the cosine of the latitude. It may be shown that this prime vertical component is also equal to the difference of astronomic and geodetic azimuths multiplied by the cotangent of the latitude. That is we have:

$$(A_s - A_g)\cot\phi = (L_s - L_g)\cos\phi$$

or

$$A_g = A_s - (L_s - L_g)\sin\phi$$

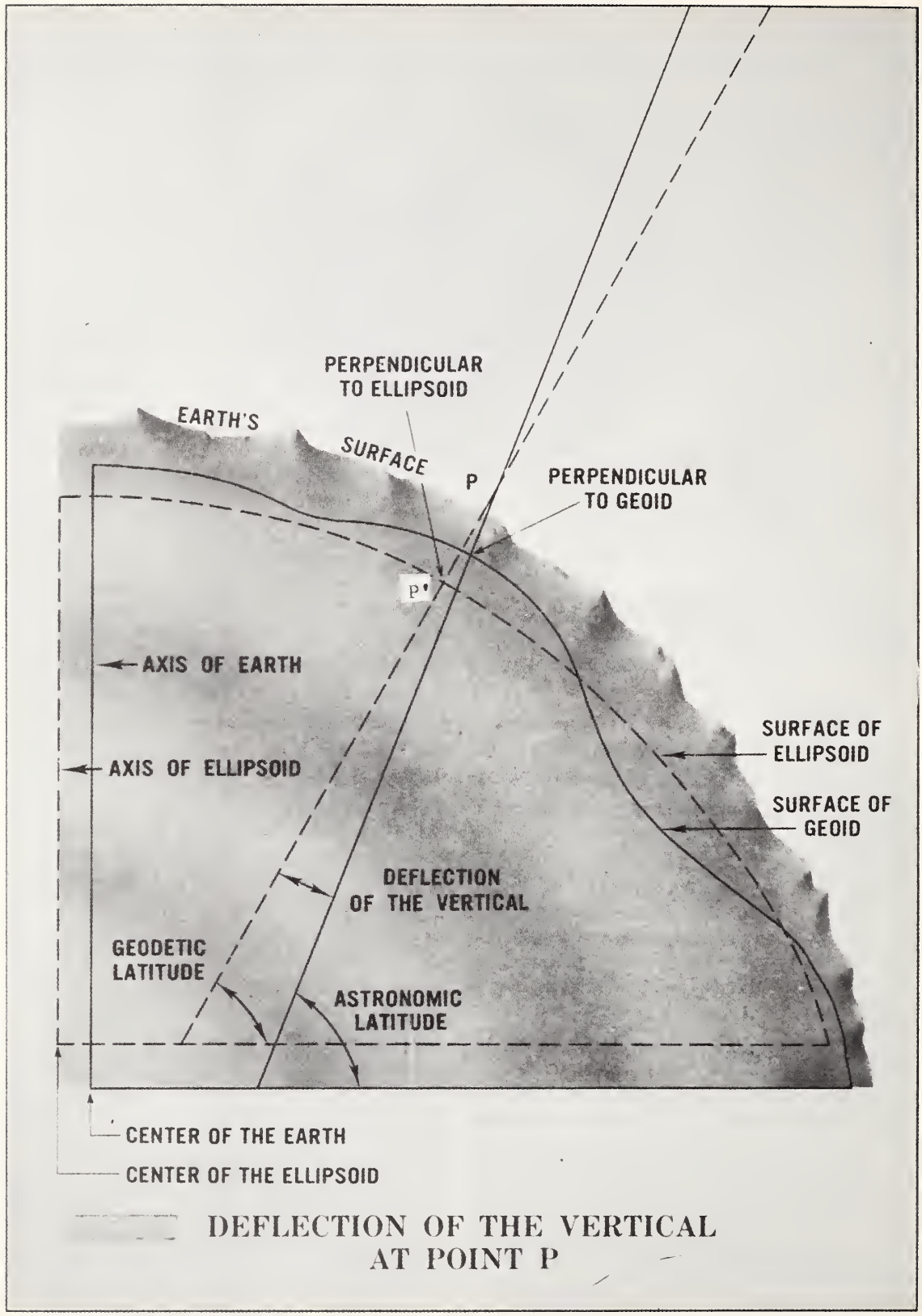


FIGURE 3.—Relationship of geoid, ellipsoid, and deflection of the vertical. (Adapted from: *Geodesy for the Layman*, Aeronautical Chart and Information Center, U.S. Air Force, St. Louis, Mo., October 1959).

where ϕ is latitude, (A_s, A_g), (L_s, L_g) are respectively (astronomic and geodetic azimuths and longitudes. This equation (Laplace) provides control of azimuths in a triangulation in the same way that accurately measured base lines control the scale.

The location of the spheroid with respect to a triangulation net is determined by comparing the geodetic and astronomical positions of the stations. Starting from a measured base line (which may have been reduced to sea level--the geoid) assuming the geographic position of one station (latitude and longitude) and azimuth to the second station, the geographic positions of the other stations are computed on the surface of the adopted ellipsoid. Simultaneously or concurrently the astronomic positions of many of the stations are determined (Laplace stations). The differences, astronomical minus geodetic (A - G), in latitudes, longitudes, and azimuths are determined for each Laplace station. These differences and their manner of distribution are studied to deduce the corrections to the assumed initial position to reduce the algebraic sum of the quantities (A - G) to a minimum. If these differences were due wholly to errors in the assumed geographical coordinates of the initial point, it would be possible to reduce (A - G) to zero, but a part of this difference is due to local deviation of the vertical or the difference in slope of the geoidal and spheroidal surfaces. The most that can be done is to shift the initial (or place the spheroid) so that (A - G) will be a small quantity. The remaining values of (A - G) at the different stations, after a recomputation, indicate the slope of the geoid with respect to the spheroid. Thus the cumulative error in position caused by the deviations of the vertical cannot be entirely reduced by astronomic observations. (The geometric mode of artificial earth satellite triangulation, in which the satellite is photographed against star backgrounds, eliminates this error source).

Even a brief account of the history of the figure of the earth must include George Gabriel Stokes, who in 1849, read a paper before the Cambridge Philosophical Society entitled, "On the variation of gravity at the surface of the earth." *He anticipated the drawing of contour maps of the geoid referred to some spheroid* analogous to ordinary topographic contour maps. But his formulae required an accurate knowledge *of the values of gravity all over the surface of the earth* (actually in terms of gravity anomalies which are the differences at specified points between observed and theoretical values).

In 1928, Vening Meinesz derived a mathematical expression, based on Stokes' work, whose tabulation made possible computations of the deviations of the vertical in much the same way as the geoid warpings. But both the Stokes and Meinesz techniques require an ideal reference ellipsoid, that is one with its center at the center of mass or volume of the earth (for Stokes' theorem these are the same) and with its axis parallel to the earth's axis of rotation. Stokes' treatment assumed the earth a sphere, but the error introduced by neglecting the flattening is not large. The Russians have developed some highly complicated formulas for dealing with it [Lambert, 1950].

In Germany, Bessel introduced standards of accuracy comparable to those of the present time. The method of least squares, investigated earlier by Gauss (the survey of Hanover) and published by Legendre in 1806 provided a procedure for determining the dimensions of the spheroid best adapted to represent as closely as possible all the observations under consideration, regardless of the number of arcs included. Thus there emerged the following methods of determining the figure of the earth: measurement of the lengths of arcs (meridians, parallels, oblique arcs) on the earth's surface combined with the determination of the astronomical positions of points on these arcs; the measurement of lengths in a network of triangles which covers an area, combined with astronomical positions; and the measurements of the variation of the force of gravity in different parts of the surface of the earth. The first two methods give the form and size, but the third gives only the form. For example the Clarke Spheroid of 1866, on which the North American Datum is based, was deduced from a least squares adjustment procedure of French, English, Russian, South African, Indian, and Peruvian arcs with corresponding astronomical positions.

In 1923 the Vaisala comparator appeared which uses a light interference method of measuring distance with an accuracy of 1 in 10,000,000. Bergstrand in 1947 reversed Fizzeu's process for measuring the speed of light by inventing the Geodimeter which uses the known speed of light to measure distance. In 1956 the Tellurometer was developed in South Africa specifically for making base line measurements by phase comparison of radar frequencies. Other instruments have appeared employing high frequency electromagnetic radiation for distance measurements. The use of these "microdistancers" has elevated trilateration and traverse to the respectability of triangulation and changed greatly the complexion of conventional geodetic operations. The adoption in 1960 by the General Conference on Weights and Measures of the definition of the meter as 1,650,763.73 wavelengths of the orange-red line of krypton 86 replaced the platinum-iridium meter bar as standard.

It was the adaptation by reversing the function of some World War II electronic positioning systems for bombing, of which the best known is shoran with its more recent improvements called Hiran and Shoran, which enabled connection of

YEAR	AUTHOR	1/F	A (METERS)	COUNTRY
1687	NEWTON	230	-	
1690	HUYGENS	578	-	
1789	LEGENDRE	318	-	
1799	GEN.COMM.FOR WEIGHTS & MEASURE	334.3	6,375,739	
1810	DELAMBRE (1)	311.5	6,376,428	
	DELAMBRE (2)	308.7	6,376,523	
1819	WALBECK	302.8	6,376,895	
1828	SCHMIDT	297.7	6,376,959	
1838	EVEREST	300.8	6,377,253	INDIA
1841	BESSEL	299.2	6,377,397	JAPAN
1847	EVEREST	311.0	6,376,634	
1849	AIRY	299.3	6,377,491	GREAT BRITAIN
1856	JAMES & CLARKE	297.7	6,377,936	
1858	CLARKE	294.3	6,378,294	
1863	CLARKE	294.4	6,378,288	
	PRATT	295.4	6,378,245	
1866	CLARKE	295.0	6,378,207	NORTH AMERICA
1868	FISCHER	288.5	6,378,338	
1880	CLARKE	293.5	6,378,249	FRANCE, AFRICA
1891	HARKNESS	300.2	6,377,972	
1907	HELMERT	298.3	6,378,140	
	HAYFORD	297.8	6,378,283	
1909	HAYFORD (1)	297.0	6,378,388	INTERNATIONAL (EUROPE)
	HAYFORD (2)	298.2	6,378,062	
1929	HEISKANEN	298.2	6,378,400	
1938	KRASSOVSKY	298.3	6,378,245	RUSSIA
1948	JEFFREYS	297.1	6,378,099	
1956	HOUGH	297.0	6,378,270	

FIGURE 4.—Principal determination of earth ellipsoid parameters, 1687-1956.

triangulation nets across some of the seas and execution of large nets of geodetic control by the process of trilateration as in northern Canada. Flare triangulation and occultations of stars by the moon produced some meager results but the use of solar eclipses for connection in 1945, 1947, and 1954 were practically a failure due to adverse weather at observing sites and instrument troubles. The next eclipse of value will be in 2151 [de Jong, 1963]. Less interest is being shown in these methods since the advent of artificial satellites.

The confusion in converting to a common scale the various units of linear measure as the toise, meter, foot, varra in the adjustment of arcs in the several countries to a common datum for obtaining a figure of the earth, no doubt accounted for a great deal of the variation in the values of the flattening and equatorial radius. With the increased use of least square adjustment procedures, the weight values to be given to the several data segments were (and still are) largely the choice of the investigator as well as the distribution function used to extrapolate or interpolate from the meager supply of useful measured values (particularly true of gravity values). Figure 4 gives the principal published ellipsoid parameters from 1687 to 1956. Note the value for 1/f of *298.2* obtained by Hayford in *1909* and by Heiskanan 20 years later. The value *298.3* was obtained by Helmert in *1907* and by Krassovsky 31 years later. Since Meinesz did not develop his three pendulum apparatus for gravity measurements in submarines until 1923, Hayford and Helmert obtained their values with no sea gravity values and Heiskanan must have had very little. *These numbers 298.3, 298.2 are important because they are the presently accepted upper and lower limits of the values of the flattening as obtained from artificial earth satellite observations.* Note also from figure 4 that the equatorial radius, *a*, has been known correct to four significant figures since 1856.

THE CONTRIBUTION OF SATELLITE ORBITS

Dynamic. The principal effect of the earth's flattening on a satellite orbit is to make the plane of the orbit rotate about the earth's axis in the direction opposite to the satellite's motion, while leaving the inclination of the orbit to the equator practically constant. The rate of rotation of the orbit plane can be accurately measured by allowing the rotation to build up for several months so that it is greater than 360°. For the near equatorial orbit of a close satellite, the orbit plane rotates at about 10° per day reducing to about 3° per day for an orbit inclined 60° to the equator. If the satellite position is measured to an accuracy of about 5 km the rate of rotation can be found correct to about 1 part in 10,000. The rate of rotation provides a measure of the flattening, which can then be obtained correct to 1 part in several thousand. By combining existing geodetic data with that from several satellites, some new world ellipsoid determinations have emerged. Some of these combine arc, gravity, astronomic, and satellite data [Kaula, 1961]. Two which have been adapted for practical use are:

1/f	*a* (meters)	
298.3	6,378,165	Australia, [Lambert, 1962].
298.3	6,378,166	NASA, Mercury Datum, Fischer, 1964 [Goddard, 1964].

Comparing the International and Fischer Spheroids, the International meridian from equator to pole is 262 meters longer. Although negligible from a practical standpoint, this is important to the geodesist.

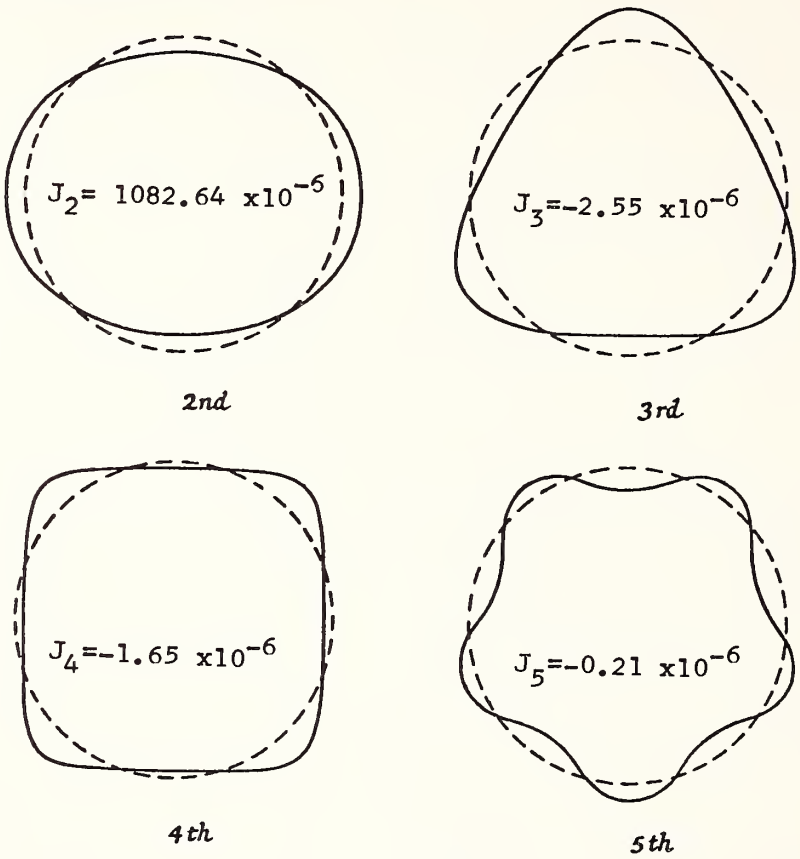
Because of the mass of the earth's atmosphere [Verniani, 1966], the equipotential surface to which an artificial earth satellite responds just clears the peak of Mount Everest. The gravitational potential U_o in geocentric latitude θ at distance r from the center of the earth, independent of longitude, is given by

$$U_o = (GM/r)\left\{1 - \sum_{n=2}^{\infty} J_n (a/r)^n P_n(\sin\theta)\right\}$$

where a is the equatorial radius, G is the gravitational constant, M is the mass of the earth, [Caputo, 1963]. The J_n in U_o are constants to be determined and P_n is the Legendre polynomial of degree n. This potential form, U_o, assumes that the basic geoid is spherical (homogeneous in layers) represented by the term GM/r, and the infinite series terms are zonal harmonics or perturbations, actually departures from the spherical form. The most important term of the infinite series is the first with coefficient J_2 (second zonal harmonic coefficient) which results from the earth's flattening causing the meridional section to be elliptic in shape with small eccentricity. The third zonal harmonic with coefficient J_3 corresponds to a slightly triangular shape; the fourth, J_4, to slightly square shape; the fifth, J_5, to slightly pentagonal shape and so on. Figure 5 shows these pictorially and greatly exaggerated. Note that the numerical value of J_2 is by far the largest, being over 400 times greater than any of the others, which means that the flattening is by far the most important feature of the shape.

By combining an indefinite number of these harmonics it is possible to build up any shape of

The values of J_2 to J_5 are from SAO Special Report No.198,GEOMETRIC STRUCTURE OF THE EARTH'S GRAVITATIONAL FIELD AS DERIVED FROM ARTIFICIAL SATELLITES, W. Köhnlein, Jan.1966,page 108.The values are those of Kozai(1964).



$$U_o = (GM/r)\left\{1 - \sum_{n=2}^{\infty} J_n (a/r)^n P_n(\sin\theta)\right\}$$

With longitude dependent terms ($C_{no} = -J_n$)

$$U = (GM/r)\left[1 + \sum_{n=2}^{\infty}\sum_{s=0}^{n} (a/r)^n P_{ns}(\sin\theta)\{C_{ns}\cos s\lambda + S_{ns}\sin s\lambda\}\right]$$

FIGURE 5.—Form of the 2nd to 5th harmonics.

earth and any gravitational field (symmetrical about the earth's rotational axis). If we wish to do the converse, that is study the gravitational field or the earth's shape, a series of the type, U_o, is set up and the terms separately evaluated under the assumption that the early terms in the series are the largest. This procedure has been followed and relatively good values for the coefficients, J_n, have been obtained for the second to seventh harmonics and tentative values for higher ones [Yionoulis, 1966].

It had been suspected long ago that the earth was not symmetrical about its rotational axis and at least 22 triaxial ellipsoid approximations have been made between 1859 and 1961 [Heiskanen, 1962]. Clearly in order to study the problem, the mathematical model of the gravitational potential must include longitude dependent terms. The form becomes then

$$U = (GM/r)\left[1 + \sum_{n=2}^{\infty} \sum_{s=0} (a/r)^n P_{ns}(\sin\theta) \left\{C_{ns} \cos s\lambda + S_{ns} \sin s\lambda\right\}\right]$$

where λ is longitude (positive eastward). The P_{ns} are the associated Legendre functions; C_{ns}, S_{ns} are numerical coefficients. The coefficients J_n defined in the original U_o become, in the more general U, the coefficients $-C_{no}$.

By referring the satellite orbit to a geocentric coordinate system and assuming that the basic orbit is an ellipse (true for a meridional orbit), the asymmetric gravity field, for inclinations other than 90°, disturbs the instantaneous or osculating elliptic orbit at each orbit point. The perturbative effects of the asymmetric gravity field on the parameters of the instantaneous ellipse (major semiaxis, eccentricity, inclination, etc.) are related to the coefficients in the gravitational potential through a "disturbing" function of U. By truncating the infinite series arbitrarily for the number of coefficients to be considered; orbital data from several satellites, of different heights and inclinations, allows evaluation of the coefficients of the C_{ns} and S_{ns} from the several equations relating them. There are almost as many variations in actual procedures as there are investigators in the field. For close satellites the perturbations due to air resistance must be accounted for and corrections for luni-solar perturbations are usually made [Mueller, 1964]. A recent computation, based on observations of several satellites by the Smithsonian Baker-Nunn cameras, evaluated 44 tesseral harmonic coefficients of the gravitational field [Kaula, 1966].

The existence of second and higher order tesseral harmonics in the gravitational potential, while interesting to geodesists, will probably not result in adoption of a triaxial ellipsoid of reference. In 1963 an extensive study of the gravity field of a rotating triaxial ellipsoid questioned the advantage of using a triaxial gravity formula for geodesy [Caputo, 1963]. But the geoid contours with respect to a reference ellipsoid can be mapped as anticipated by Stokes. Many of these world geoidal mappings have appeared. A recent study [Anderle, 1966], based on data from the Navy Doppler satellite tracking system, gives several such mappings based on several analysis methods and inclinations of several satellites. It is concluded, in the report, that geoid undulations are provided by the system to an accuracy of about 20 meters. It is expected that 10 meter accuracy will be obtained for geoid features in the future because of an increased number of gravity coefficients and satellite inclinations to be included. Figure 6 is one of the geoid contour maps at 10-meter intervals.

The procedure for evaluating the first few coefficients in the infinite series expansion for the gravitational potential involves neglecting all higher order terms after the first few. This seems justified because the first few are larger (see fig. 5). But the sum of the ignored terms has never been effectively estimated, granted that the geoid is not like a "lumpy potato." The procedure would seem more justified if the higher harmonics died away rapidly but results so far obtained contradict this. Then the lower harmonics obtained in this way are used in obtaining the tesseral harmonic coefficients [Cook, 1963]. The level surface corresponding to satellite motion is just clear of Mount Everest and the procedures for reducing to the geoid are apparently satisfactory. But when geoidal mapping as obtained from the admittedly sparse surface gravity measurements is compared to that from satellite data alone, the agreement is not necessarily good as shown in figure 7 [Runcorn, 1964]. A recent study of the methods of analysis of gravity to estimate the low harmonics revealed serious inconsistencies between results as derived from surface gravity measurements through classical methods and those derived from artificial earth satellites and concluded that a complete gravity survey will be needed for the tesseral harmonics [Jeffreys, 1961]. Should it be that the useful gravity measurements over the entire surface (when obtained) sustain reasonably well the projected geoid as available now from meager surface values we can look then to the reduction methods or the interpretation of the satellite values. It could be that the neglect of the cumulative effect of higher order terms in the presently used mathematical model of the gravitational potential is the cause

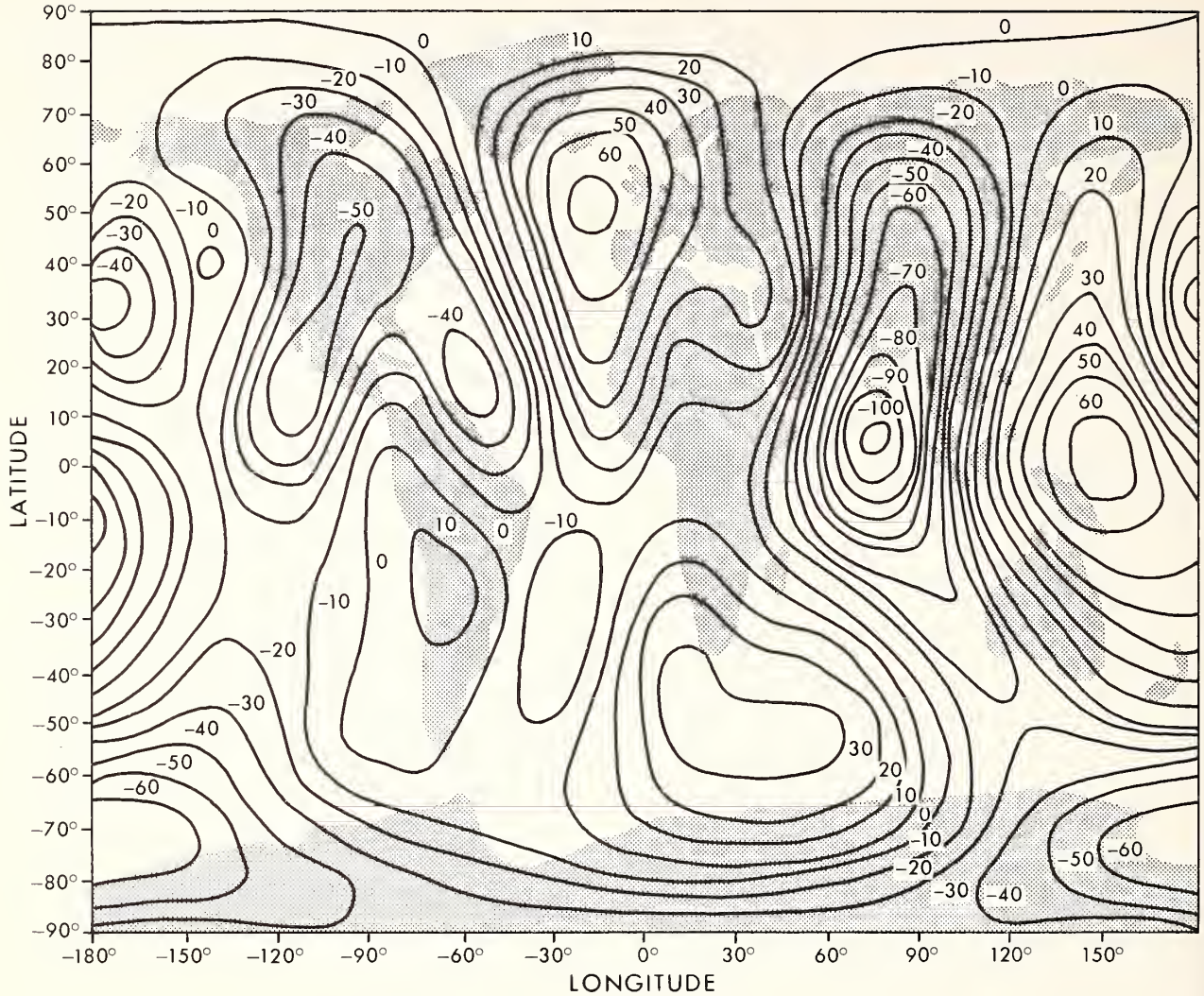


FIGURE 6.—Geoid heights at 10-meter intervals for most significant 50 parameters. (After Anderle, March 1966).

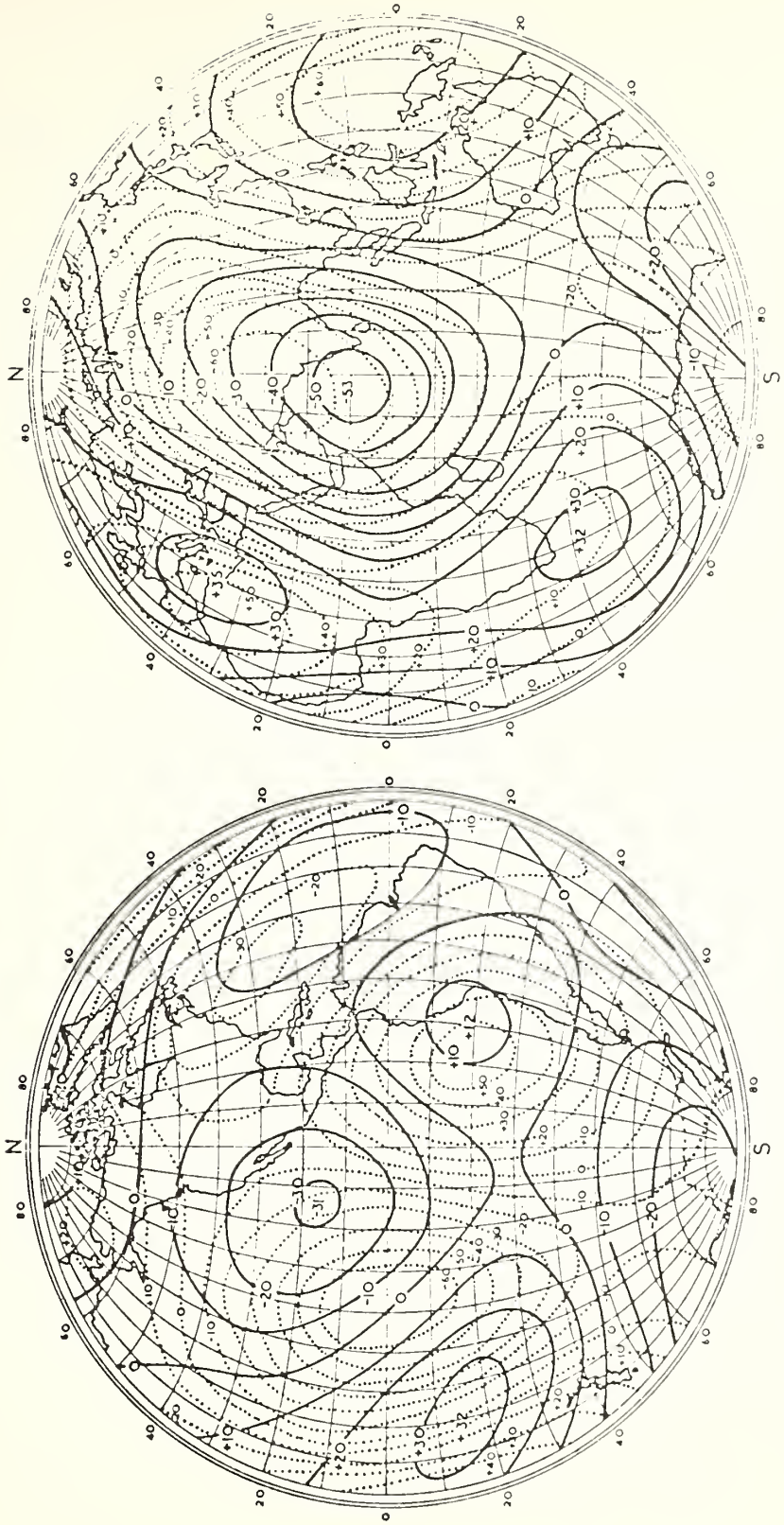
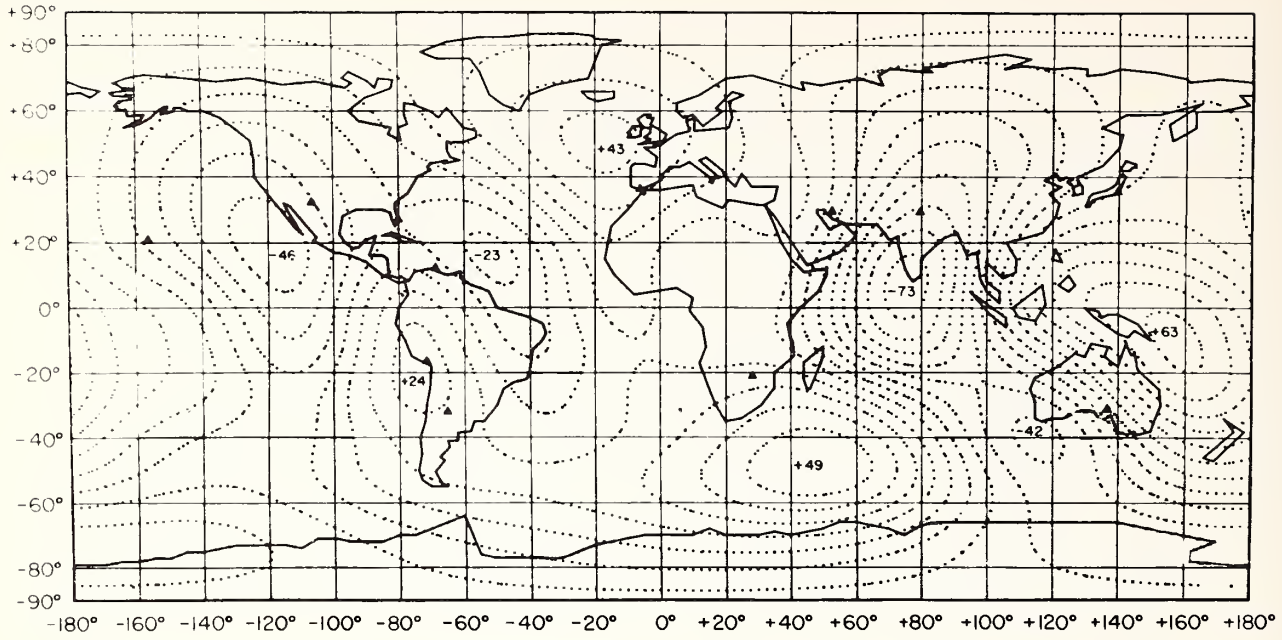


FIGURE 7.—Comparison of geoidal mappings as obtained from satellite data (Izak, 1963) and surface gravity measurements (Uotila, 1962). Geoid contours in meters; solid lines from satellite data; dotted lines from surface observations.



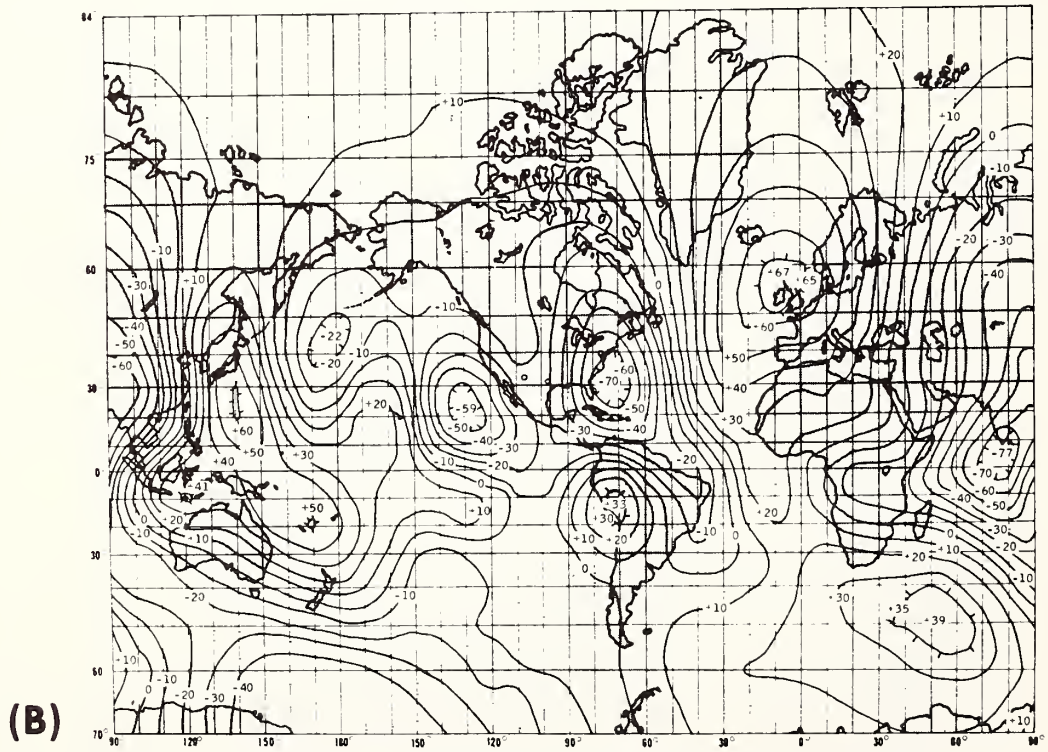


FIGURE 8.—Comparison of geoidal mappings as obtained from (a) Baker-Nunn camera observations of 11 satellites (Izak, 1965) and (b) Doppler tracking of 5 satellites (Guier and Newton, 1965).

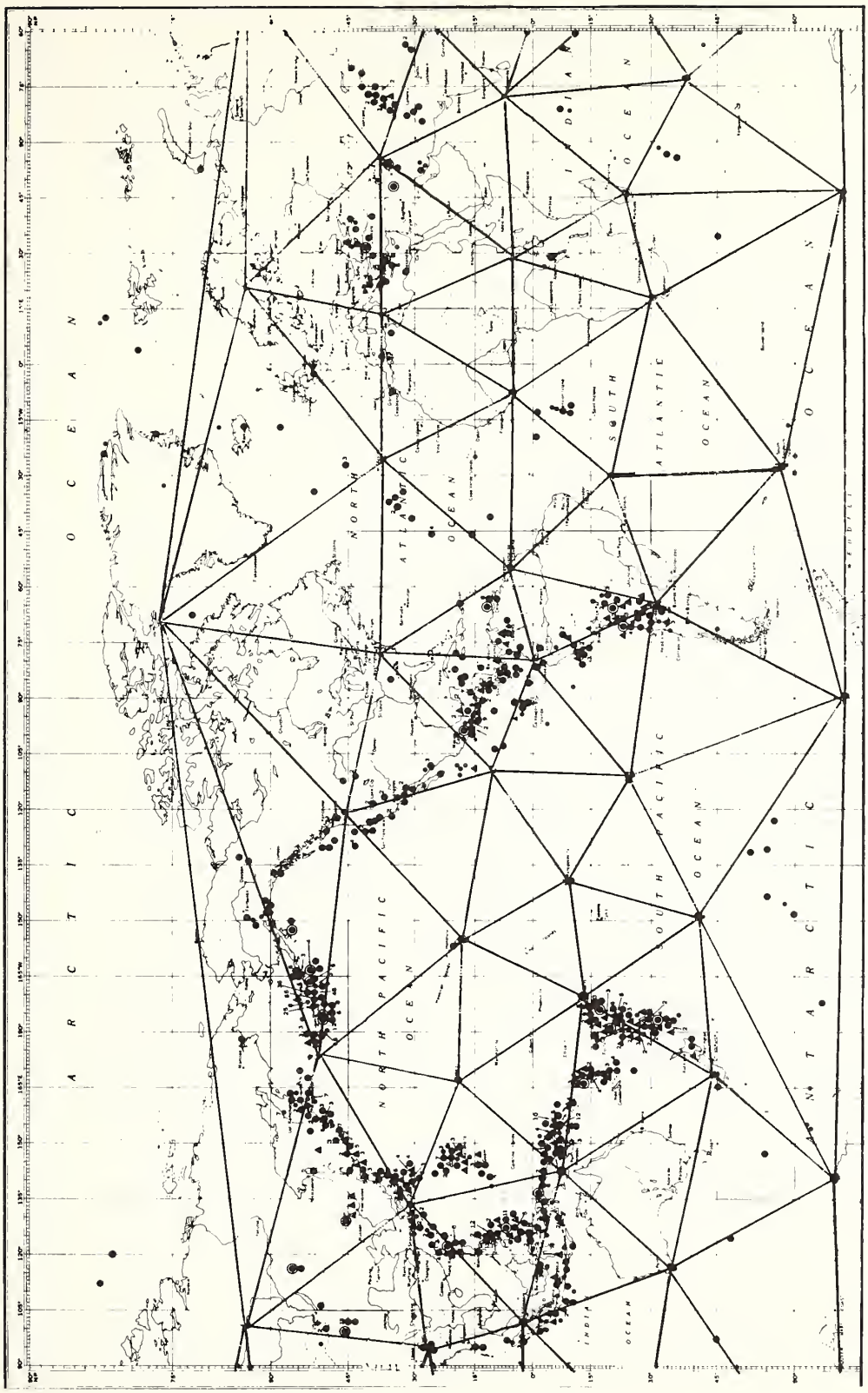


FIGURE 9.—Worldwide accurate triangulation net to be established by satellite geodesy. Distribution of earthquakes (dots) indicates seismic belts.

of the differences as reported among the several satellite orbit analyses and these compared to analyses of surface gravity values. For the present there is some disagreement in the first few coefficients of the zonal harmonics as obtained from satellites. There are larger variations in the tesseral harmonics and it is perhaps pointless to compare them numerically. Perhaps the best determination of the second and third order tesseral harmonics has been obtained by NASA from analysis of the tracking records of three synchronous (nearly geostationary) satellites. The necessary drift accelerations were deduced relative to several locations around the equator [Wagner, 1966]. Figure 8 gives a comparison of the geoidal mappings as obtained from the Baker-Nunn camera system and the Doppler tracking system.

Geometric. An astrophotogrammetric method of using artificial satellites involves photographing the satellite against a star background from the two or more earth based stations. The successive positions of the satellite among the stars on each time correlated set of exposures on the photographic plate are deduced from the ephemerides of the stars after a set of comparator measured distances on the plate between the satellite and a selected set of the background stars have been adjusted by a least squares procedure. Transforming the "plate coordinates" thus obtained into equivalent right ascensions and declinations, and with the accurately measured base lines between the initial camera sites (usually in a known triangulation net) by a set of space triangles (a common vertex on the satellite), the chord distances and directions between the known and unknown earth based stations can be computed. For higher satellites, oceans can be bridged and intercontinental datum ties effected. Such a system is clearly independent of the deviations of the vertical.

A United States Geodetic Satellite Program has been formed involving the Department of Defense (AMS), ESSA (C&GS), and NASA. Its objective is to establish a world interconnected polyhedron of accurate chord distances between the continents and island areas as shown in figure 9. The method was proved feasible through preliminary observations on Echo I and II by means of the C&GS BC-4 camera systems. The official program was initiated with the launching of Pageos I. Twelve BC-4 camera systems, operated by C&GS and AMS, were ready on stations. These cameras are probably the most accurate mobile optical systems available [Schmid, 1966; Swanson, 1965].

Besides tying all the geodetic nets on all the land masses together very accurately (at least with an error of no more than 1 in 500,000), the net will provide an absolute and identical scale for the entire earth in terms of the physically defined meter. It will thus provide an independent determination, on a world wide basis, of the ellipsoid parameters. It will tie together accurately some of the Baker-Nunn camera sites, and Navy Doppler tracking stations providing an accurate scale reference for satellite orbits. By periodic reobservation it may settle the question of drifting continents and expansion or contraction of the earth. It connects the principal seismic belts and will aid in earthquake studies. It will tie together accurately the electronic beacons of navigational systems. *It will form a basic control in which to fix the subnets of Marine Geodesy.* It is interesting to note that the Russians have proposed the establishment of an analogous world polyhedron of accurate chord distances and directions from observations of high synchronous satellites in equatorial orbits [Zhongolovich, 1966].

THE CHANGING COMPLEXION OF GEODESY

The province of geodesy now includes the establishing of horizontal and vertical control nets; observations of gravity over the surface of the earth; observations of secular variations in latitude, gravity, and earth tides; special very accurate geodetic frameworks for referencing special studies, the launching facilities for rockets (and space vehicles); extension of astronomic investigations associated with astro-geodetic operations to include at least that part of celestial mechanics concerned with orbit theory of the artificial satellites used for geodesy and navigation.

To accomplish these tasks an array of new instruments and instrumentation systems are or are becoming available such as air and seaborne gravity meters; the "microdistancers"—Tellurometer, Electrotape, etc.; satellite observing systems--optical: Baker-Nunn and Wild BC-4; electronic--Navy Doppler, and AMS SECOR which makes multitudinous range measurements from satellite to ground stations; lasers for altimeters, distance measuring, light source in geodimeters, satellite tracking. To handle the plethora of data measurements being generated, new data reduction equipments have been developed or adapted. Large computing systems and new numerical analysis techniques are required. These briefly reflect the complexity and magnitude of the activities included in modern geodetic operations.

The physical reality, now in view, of a worldwide three dimensional reference polyhedron of accurately determined chords connecting various parts of the lithosphere has renewed discussions involving the very foundations of geodesy. Some advocate avoiding the determination of the geoid maintaining that it is an unsolvable problem and unnecessary. It is suggested that geodetic lines or geodesics computed on the surface of a reference ellipsoid be replaced by computations of chords on the lithosphere in a worldwide three

dimensional Cartesian coordinate system with origin a point representing the center of mass and one axis the rotational axis of the earth. Finally the theory of adjustments should be based on modern mathematical statistics instead of the vague concept of errors [Hirvonan, 1961].

If enough useful gravity values can be obtained in many of the land areas, particularly the polar regions and desert areas, on the surface and bottom of the oceans, and above the earth at least to the height of Mt. Everest, we may be able to compare effectively the gravity fields as obtained by satellites and by direct measurement. Besides satisfying the requirements of Stokes' theorem, it could lead to new corrections for satellite orbits that might increase the prediction capability allowing ephemerides to be constructed months in advance. This would materially reduce the problem of updating the orbit for Doppler navigation satellites.

GEODESY AND THE OTHER EARTH SCIENCES

For the purpose of the International Upper Mantle Project, the upper mantle includes the crust of the earth and its associated tectonic and geophysical phenomena. In direct support of the Project, geodesy is being called upon for accurate geodetic control and accurate position determination of all land, sea, and air observing stations employed in the various scientific investigations. This consequently imposes the requirement for operational surveys over broad areas and for detailed traverses and fundamental measurements in regions of fault lines, magnetic and gravitational anomalies, and other geophysical features of special interest. Figure 10 shows such geodetic support as provided in the United States. Similar support is being obtained for the other continents. But for the comparative study of the structure and development of different tectonic zones of the globe, the distinguishable zones in the oceans as deep basins, trenches, submarine ridges, oceanic islands, island arcs and transition zones between the continents and the oceans, we must look to the development of *Marine Geodesy* to fulfill the requirements except for perhaps a few accessible regions. Useful gravity measurements have recently been obtained at a depth of 900 meters, off the coast of southern California, with a modified Lacoste-Romberg underwater gravimeter [Beyer et al, 1966]. Many research submersibles are appearing with the increased emphasis on oceanography. The Lockheed Deep Quest has an operating depth of at least 2,500 meters. Magnetometers sensitive enough to reveal deposits below the ocean floor are under development. President Johnson is studying a proposal to build an underwater merchant fleet of atomic powered cargo carrying submarines which can travel below the disturbed interface between the ocean and the atmosphere, free of waves, windstorms, and ice [Washington Post, 1966]. But underwater the navigator must have complete maps of the bottom topography, the gravimetry, and magnetic anomalies. Atom powered beacon systems will be needed for regular routes under the sea. Hence the practical need for accurate geodetic control and gravity values in ocean areas.

We have noted the scientific value of gravity measurements over the oceans bottom and surface and at mountain heights, with respect to geoidal mappings. But variations in the gravitational field of the earth, when corrected for the effects of latitude, elevation, and topographic relief, are a function of density variations in the crust and upper mantle. Where the gravitational effects of local geology can be ascertained from surface or subsurface geologic mapping, the residual gravitational variations provide a means of measuring the strength of the materials in the upper mantle and crust. Combined with the result of seismic investigations, such regional gravity variations also reflect variations in the depth to the mantle.

Finally some quotations from *Effective Use of the Sea*, Report of the Panel on Oceanography, Presidents Science Advisory Committee, The White House, June 1966. On page 21 we find that "Drilling and construction activities require the ability to locate a bottom point to a position of better than 10 feet when referred to a point on the surface in the same vicinity." On page 23 we have that "Good topographic and geologic surveys are needed. These surveys should first extend to the Continental Shelf of the United States. Second priority is given to other continental shelves, third priority to the deep ocean of United States, and fourth rank to other deep-ocean areas. A major problem is to reduce the time and cost of surveying without reducing precision of the final result." Can Marine Geodesy meet the challenge?

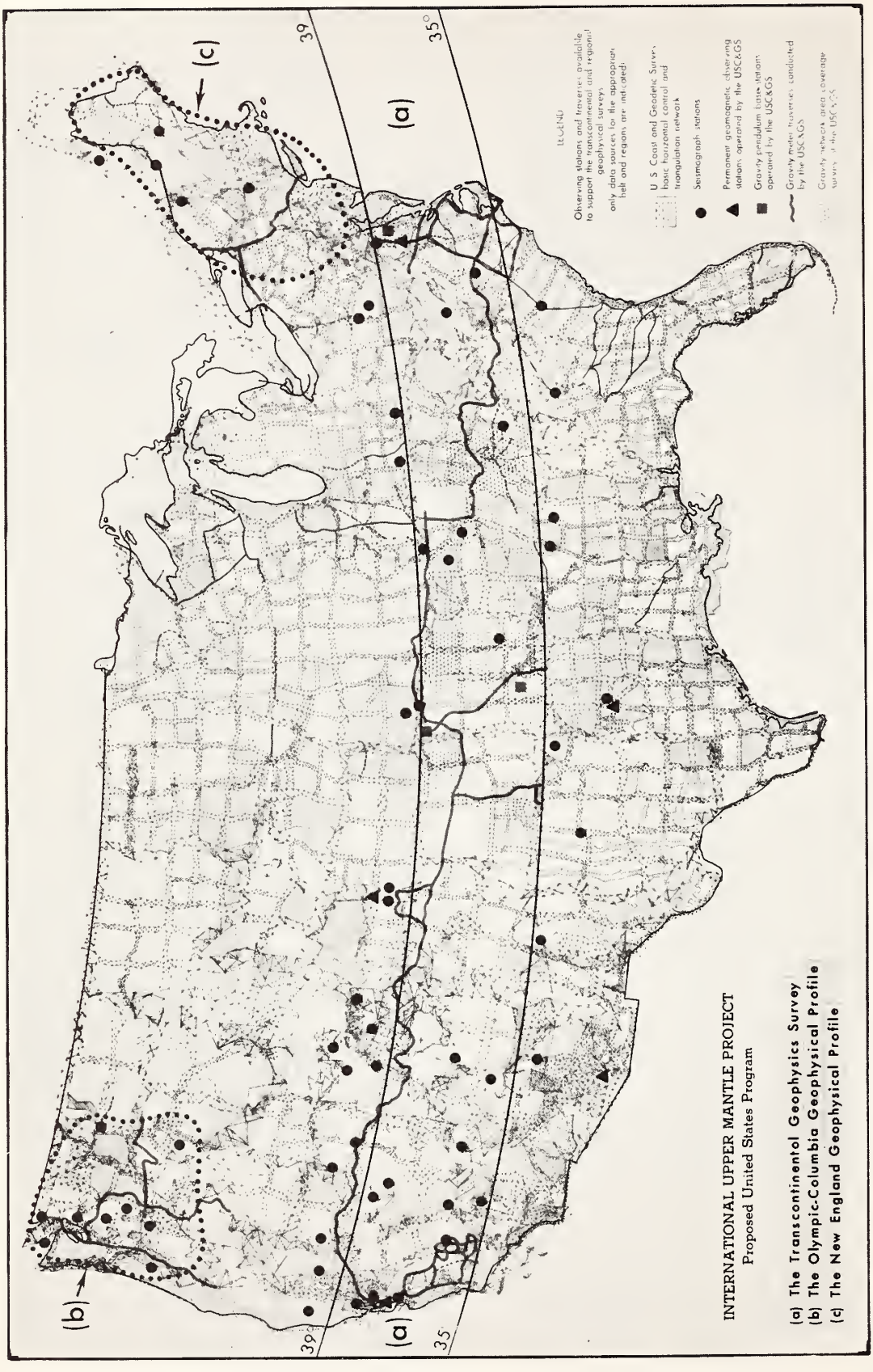

INTERNATIONAL UPPER MANTLE PROJECT
Proposed United States Program
(a) The Transcontinental Geophysics Survey
(b) The Olympic-Columbia Geophysical Profile
(c) The New England Geophysical Profile
(a)
(b)
(c)
39°
35°
LEGEND
Observing stations and traverses available to support the transcontinental and regional geophysical surveys; only data sources for the appropriate belt and regions are indicated:
U.S. Coast and Geodetic Survey, basic horizontal control and triangulation network
Seismograph stations
Permanent geomagnetic observing station operated by the USC&GS
Gravity pendulum base station operated by the USC&GS
Gravity meter traverses conducted by the USC&GS
Gravity network area coverage survey of the USC&GS

FIGURE 10.—Geodetic control network of USC&GS and proposed United States program for International Upper Mantle Project.

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The Concept of Marine Geodesy

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To formulate a definition of marine geodesy that is inclusive enough to satisfy all concerned would not be easy. I will just say that marine geodesy is the science which deals with geodetic measurements and their adjustment, leading to the establishment of basic marine control points (horizontal and/or vertical) for hydrographic, bathymetric, geophysical, and oceanographic mapping and for improving navigation systems that are generally employed in marine positioning.

The vast economic resources of the oceans and their importance in national defense forces man to depend more and more on the oceans. However, before we can intelligently explore the oceans and effectively use their resources, we must be able to map them clearly. The science that is basic for ocean mapping and for effective use of the sea is, of course, marine geodesy—the subject of this paper and this Symposium.

GOALS OF MARINE GEODESY

The overall mission of marine geodesy is, like that of other branches of geodesy, to determine the size and shape of the earth and its gravity field. The goal of geodesy has been to establish a World Geodetic System (WGS) of high accuracy to permit worldwide successful operations for scientific, economic, and military purposes. Giant forward steps have been taken in the United States and other countries to achieve this goal. Measurements across continents using land and island bases have been made. In the United States, a form of WGS was developed, based mostly on land geodesy. Satellite geodesy has more recently been employed to improve this WGS [Frey, 1966]. The U.S. satellite geodesy program headed by NASA, with participants from the Department of Defense, the military, the U.S. Coast and Geodetic Survey (ESSA), and other scientific organizations, is aimed at the establishment of a more accurate WGS. Associated with this is the equally important and large task of worldwide gravity measurements. However, the drawback of the satellite program, although it has connected continents and islands together, forming several high-accuracy land control points, and has brought together the world geodetic datums, is that it has neglected the establishment of an oceanic geodetic system with several marine control points connected to the WGS.

When it is considered that the land masses occupy less than 30 percent of the total surface of the earth, it can be seen immediately that our geodetic goals are far from being achieved. Attention must therefore be focused on the other 70 percent of the earth's surface which is covered with water.

In advancing its purpose, land geodesy determines accurately the position of points on the surface of the earth in an absolute coordinate system. These points are useful as controls for mapping and other precise operations. The accuracy of land maps is highly dependent on the accuracy and quality of the horizontal and vertical control provided by geodesy. Similarly, for marine geodesy to achieve one of its major goals, the positions of points in the oceans must be accurately established and the gravity field over this three-fourths of the earth's surface must be measured in more detail than is now the case.

The practical goal of marine geodesy is, of course, mapping. It can also help solve the numerous marine problems associated with ocean mapping by communication and translation of theoretical and scientific knowledge into practice. Problems that might be solved are involved, for example, in the exploration and exploitation of ocean resources, in precise marine navigation and positioning, in complex engineering and recovery operations and, most important, in effective national defense.

Achieving this practical purpose would involve not only bringing together industrial concerns and research, academic, and governmental communities, but also communicating among these groups so that the best talent for the solution of these problems can be identified and utilized. As evidenced by the many industry representatives attending this Symposium, there must be many

industrial problems which require basic geodetic knowledge for solution.

MARINE CONTROL POINTS

A natural question to ask of a marine geodesist is "What is a control point?"

A marine control point is a point of fixed coordinates located on the ocean floor. Its exact position is determined to a prescribed accuracy in terms of absolute coordinates (i.e., geographic latitude, longitude, and elevation or depth from sea level). The control point might be represented by one or several marine geodetic markers placed on the surface of the ocean, within the ocean, or on the ocean floor. Figure 1 shows possible types of geodetic markers. These markers might, for example, be a set of several acoustic transponders or hydrophones placed in suitable locations on or immediately above the ocean floor. A transponder is composed of three basic parts: power source, electric circuitry, and an acoustic element. Underwater acoustic transponders are devices that, in response to a signal received, transmit an acoustic signal of their own. Hydrophones are also acoustic devices which only receive acoustic signals. The received signals are telemetered through cables connecting the hydrophones to a shore station, a moored buoy, a platform, or a ship. The control point could also be in the form of acoustic reflectors without power, anchored buoys, or platforms.

Whatever the hardware involved, marine geodetic markers must have the capability of acquisition and identification of signals. The acquisition of signals is dependent on several factors such as water depth, condition of water, and beam width, frequency, and power of the transducer. Power sources which can give long unattended life are, of course, desirable.

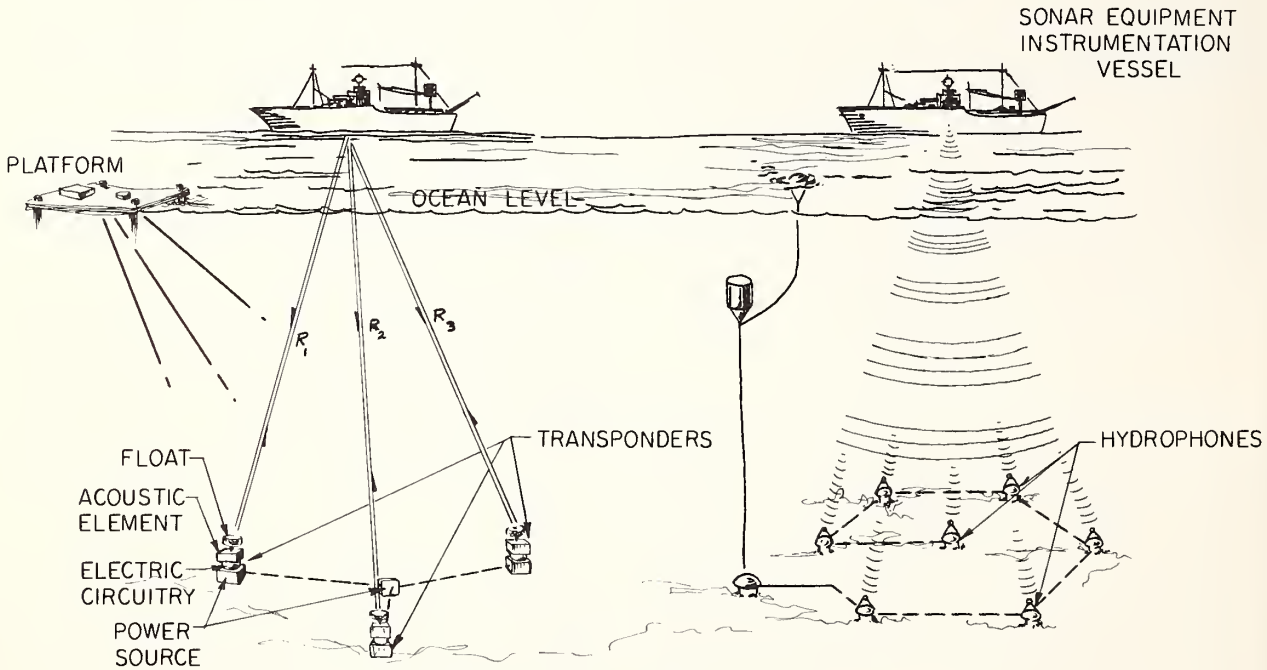

FIGURE 1.—Marine control points.

MARINE GEODETIC NETWORK

A series of these control points established in a given area, as shown in figure 2, would form a marine geodetic network analogous to land triangulation or trilateration networks. These networks would form the backbone and provide a rigid geodetic framework for the surveyed area, which could be used later for accurate mapping and charting. Various surveys could be connected and referenced to the same datum, thus making it possible to relate points from one chart to another with determined accuracy.

Marine geodetic networks can be of several orders of accuracy similar to land networks—first, second, and third, etc.--depending on the accuracy, density of control, and other conditions, although a redefinition of these accuracy orders for marine geodetic use may be required. With our present geodetic knowledge and capability, it would be in the best national interest to establish a rigid framework (geodetic network) in the continental shelf and even deeper waters now instead of conducting many unrelated and perhaps useless surveys. Only when all surveys, maps, and charts are combined into

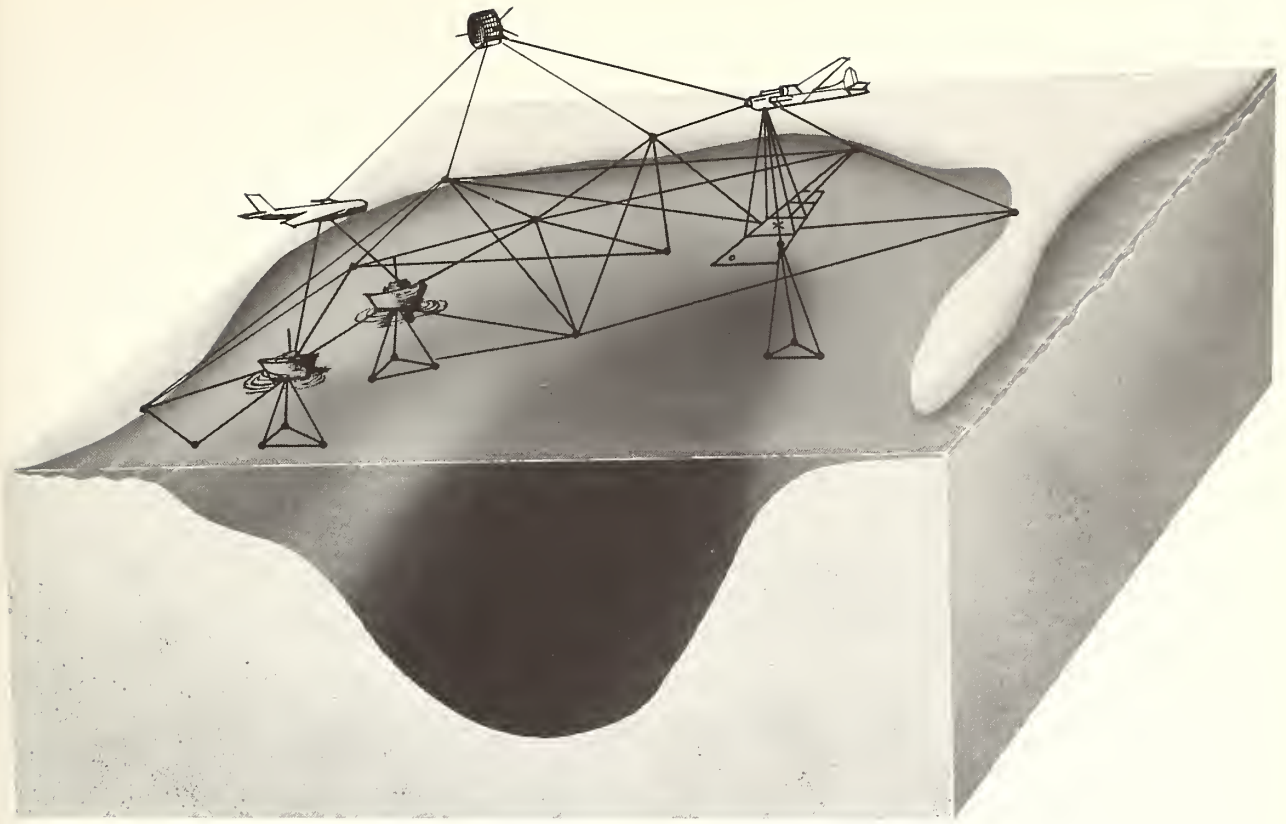

FIGURE 2.—Series of control points forming marine geodetic network.

one major network, can sound economic development and effective national defense support be assured.

The establishment of a network involves design, distance measurements, computations, and adjustments.

USE OF MARINE CONTROL POINTS AND/OR NETWORKS

Before the establishment of controls and networks is discussed, an explanation of their use is needed. Marine control points when established could serve as the bases for many ocean operations and activities. Their use in hydrographic and bathymetric surveys is essential. Such control points are also important for geophysical surveys, navigation, oceanographic and meteorological surveys, and space and defense operations.

Hydrographic Surveys

Hydrographic surveys are generally conducted in the coastal areas and sometimes extend inshore accross the low-water line. The accuracy of a nautical chart is highly dependent on the accuracy of the hydrographic survey from which it is compiled. Also, the accuracy of the hydrographic survey depends on the accuracy and adequacy of the geodetic controls.

Horizontal control is usually extended from the land triangulation newtworks through the use of electronic surveying systems. However, to provide this control with present electronic systems requires extreme care, and accuracy is often limited due to many environmental and instrumental problems. Vertical control is usually provided by tidal-station measurements.

Bathymetric Surveys

Bathymetric Surveys are conducted in the deep oceans at great distances from shore. These surveys also require geodetic control points for establishing accurate depths and accurate positions. At present, there are few electronic systems that are capable of positioning these surveys at great distances. The problem of

horizontal control is quite severe. It is not possible to reference these surveys accurately to the terrestrial triangulation system with current methods and techniques. A network of bottom-mounted fixed control points is of primary importance if we are to map and explore the various regions of the oceans. Vertical control for these surveys in the form of tidal measurements is almost nonexistent. Earlier thinking that tides are very small in the open ocean may not be correct according to the results of a recent experiment conducted by the U.S. Coast and Geodetic Survey. They succeeded in recording tides 5 feet high, at distances about 100 miles from shore. Therefore, ocean mapping must be treated in a more precise manner.

Geophysical Surveys

All geophysical surveys—seismic, gravimetric, magnetic, and others—are of great importance in the exploration and exploitation of the oceans, and they must depend on geodesy for accurate positions and reference data. In this respect their requirements are somewhat similar to those described for hydrographic and bathymetric surveys. For gravity surveys, however, there are additional requirements that must be met for obtaining accurate and useful data.

Because of the utmost importance of gravity in the accurate determination of the figure of the earth, its effect on satellite orbits and missile trajectories, and its importance for inertial navigation systems and deflection of the vertical computation, especially at sea, the Department of Defense has recently established requirements for worldwide gravity measurements using airborne, shipborne, and ocean-bottom instruments.

One of the biggest problems soon to be faced in making airborne and surface-ship gravity measurements is the lack of base stations in the open ocean to serve as controls and checks. It is easy to appreciate the importance of base stations for land gravity measurements. Without them large errors due to drift and other systematic errors would be very difficult to determine. Of course, errors also occur in land areas where the positions of measurements are precisely known. Precision is much more difficult in the open ocean. It is apparent that just by simple analogy we can qualitatively determine the importance of base stations for marine gravity surveys. The use of control points as marine gravity base stations could help a great deal in controlling our airborne and shipborne measurements. A network of such bases and a suggested approach for testing and proving its feasibility is described later in this paper.

Navigation

Marine navigation is highly dependent on the availability of at least accurate horizontal shore control for positioning of transmitters and/or receivers. Control points in deep waters could further serve as checks and means of identification of lane counts for many surveys. However, the tool most needed from geodesy for navigation and especially surveying is a "yard stick" or calibration range for calibration and accuracy determination of the many positioning systems employed in navigation. The establishment of such a range is described below.

Oceanographic and Meteorological Surveys

Control points can also be useful in conducting oceanographic and meteorological surveys. Although these surveys may not require great accuracy, control points, if available, could be useful in the systematic collection and study of data from these surveys.

Space and Defense Operations

Many other possible uses for marine control points are, of course, obvious. For example, they would be invaluable for the recovery of lost objects and also for the retrieval of space ships of present splash-down design. National defense certainly hinges also on the availability of accurate position information anywhere in the oceans.

ESTABLISHMENT OF MARINE CONTROL POINTS

There are six essential steps involved in the establishment of a marine geodetic network [Mourad, 1965]. These are planning, design, placement of equipment, measurements, computation and adjustment, and final coordinate and accuracy determination of the network.

Planning

In any operation, good planning is important to save time and costs. In marine geodesy, good planning is not only important but essential to the execution of geodetic projects. In planning, one must consider first of all the requirements and the funds that are available for execution of the project. An area may be assigned as part of the requirements or may have to be selected in the planning or after a preliminary reconnaissance survey. The final accuracy achieved in the geodetic work is often adversely affected by poor planning, which allows a substantial time lapse between the beginning of a survey, the time of measurements, and the reduction of end results to produce a map. Accuracy can be very high if planning is careful. An example of good

planning is afforded by the Florida survey by the USC&GS for the Air Force Missile Tracking Stations in 1959 [Simmons, 1960]. An accuracy of 1:400,000 was required for an area of about 4,000 square miles. Such accuracy had never been achieved before. The results obtained had a probable error of 1 part in 1,300,000, which demonstrated the extreme care used in planning and conducting the survey. In planning oceanographic surveys, existing controls, whenever available, should be used. Logistics in the establishment of marine networks would involve much more than land surveying projects. For example, ships, aircraft, and satellites might all have to be used at the same time. Operation would be extremely expensive and would have to be considered very seriously in the planning.

Network Design

The purpose of network designs (large or small) is to insure the fulfillment of the project requirements in the most efficient and economic manner. In the design of a network, care should be exercised not only to give the optimum network but also to provide an alternative solution. The lines and points forming the network should be made of equal importance so that the elimination of any line measurement due to field mishaps will not greatly affect the final accuracy. The importance of this can be appreciated when actual measurements are being made under field conditions that force deviation from a set plan. The alternative solution could be provided by adding points and lines to be observed in order to achieve the best figure.

The basic design of marine geodetic networks is a tedious job for which the designers must consider several factors. These factors may be related to:

(1) Physical parameters of a geodetic, geophysical, geological, oceanographic, acoustic, or electronic nature, and
(2) equipment and techniques appropriate to the measuring method selected.

For example, the design of a network to be established using satellite measurement techniques may differ considerably from that of an airborne-, surface-, or underwater-based network. The designer must also consider the projet requirements and establish the specifications and preliminary computations on the basis of the above factors.

The network design must consider all factors in the light of the following:

(1) Accuracy requirements,
(2) existing controls and ties,
(3) criteria relative to number of points and lines terminating at the unknown stations, ratio of observations to unknowns, determination of standard error of all points, and provision for equal weighting with varying weight possibilities yielding different degrees of accuracy,
(4) length-of-line and distance limitations, and
(5) anticipated operational conditions during equipment installation and measurements.

The strength of figure can be predicted and areas of weakness can be detected if the inverse-weight matrix method is used. This method makes it simple to use a computer for computations to yield the best configuration. The computer program should be written so that any change in the network design or configuration can be incorporated with as little effort and time as possible to achieve the new solution. The basic network design should permit maximum incorporation of growth features made necessary by integration of new systems or technological advances. It should also have the capability of growing into second- and third-order-of-accuracy networks and must certainly be based on one common reference system. Finally, the design should be evaluated for accuracy and cost effectiveness.

Placement of Equipment

On the basis of the network design and evaluation, the equipment (for example, the marine geodetic markers) providing the control points could then be placed approximately in the selected or recommended positions. For this placement, we must know more about the ocean bottom and its material properties. Pertinent geological and geophysical problems involve, for example, consideration of suitable sites and depths for placing objects on the bottom. The general and perhaps detailed topography of the sea floor must be known and areas of underwater landslides and turbidity currents must be located. Ocean sediments must be investigated in the vicinity of the sites to determine their acoustic properties and effects and the limitations they may impose on anchoring of equipment. Many other related problems such as internal wave actions, seismic activity, currents, and methods of anchoring and installation must also be considered. Also, the mathematical model must be ready during the time of equipment installation for deriving observation equations resulting from actual distance measurements and from ship positioning relative to the control points.

Distance Measurements

In the establishment of marine geodetic controls and in conducting hydrographic and bathymetric surveys, distance measurements are of great importance. We are concerned here not only with determining horizontal distances, but also with determining vertical distances. For example, depth and slant-range measurements must be

made from the surface to the bottom of the ocean. The simultaneous measurement of horizontal and vertical distances is essential for establishing marine geodetic controls and also for positioning various types of surveys.

The vertical distances, or the relative position of the ship with respect to the bottom equipment, can be measured acoustically by the transmission of signals between the ship and the bottom equipment. Figure 1 shows how this might be done. The intersection of three slant ranges, for example, would give one solution to the position. Either spherical or hyperbolic ranging techniques could be used. Other methods that could be applied involve acoustic line-crossing techniques or variations of these techniques to determine minimum distances. The use of a single-source unit is also possible if equipment for use of interferometry techniques can be provided on the ship. The selection and use of any one of the methods available would be determined by the budget and by the projet requirements for accuracy.

The measurement of horizontal distances or the determination of geographic coordinates of control points could be accomplished with any one or combination of the following systems:

(1) Surface-based systems,
(2) airborne-based systems,
(3) satellite-based systems, and
(4) underwater-and-surface-based systems.

Surface-Based Systems.—A number of surface-based electronic systems can be used to provide distance measurements and to determine the coordinates of points at sea. Several systems are available at present which are capable of measuring short ranges within 50 miles from shore. If extreme care is exercised in their application, geodetic accuracy can be obtained. At ranges of the order of 1,000 miles or more, only two systems are feasible: Loran-C and Omega (not quite operational yet). Although they are intended to extend or provide survey control, their accuracy is not satisfactory for geodetic use.

Airborne-Based Systems.—In the airborne-based category two systems are available: Shiran/Hiran and Lorac. Both can employ line-crossing techniques for distance measurements. Shiran/Hiran has been used extensively in world-wide mapping and has the capability of measuring distances of the order of 500 miles on land. Its application in the oceans is discussed in more detail by another speaker [Robson, 1966].

Satellite-Based Systems.—Three major techniques have been used on land for distance measurements and establishment of geodetic control on a global basis:

(1) Secor—uses electronic ranges measurements,

(2) Doppler—developed for long-range positioning at sea (the inverse solution of two positions yields a distance between two positions), and

(3) photographic—widely applied for geometric connection of the WGS datums.

Their actual use at sea, except for the Doppler technique, has been limited to experimental work. These systems and techniques are also discussed by other speakers.

Underwater- and Surface-Based Systems.—In contrast with previously discussed systems that use electronic techniques, these systems depend on underwater acoustics. Examples of these systems are sofar and rafos. They take advantage of the existence of a sound channel in the oceans, which permits sound to be propagated for great distances.

The application of these systems for geodetic purposes, although uncertain at present, has great promise if a new approach is used for determining some of the variables involved. For example, the determination of absolute distances between two or three sofar stations is important to eliminate one of the variables. An empirical equation for velocity of sound refractive index could be established and used as a basis for corrections of the velocity variable, which is large in underwater-measured distances.

Integration of Systems

Whichever system or technique is used in the determination of coordinates of control points in the oceans, the measurement of surface distances must be correlated with underwater measurement. The function of marine geodetic markers is similar to that of land points. Distances between ocean-bottom markers can be measured accurately by a ship acting as an intermediate platform that relates the underwater measurements to surface measurements. The main factor to be considered is the simultaneous measurement of distances between ships and distances between ships and bottom references. Timing circuits connecting electromagnetic measurement and underwater acoustic measurement could help to simplify the problem of marine measurements and increase their accuracy. In all cases of horizontal distance measurement, whether the system used is satellite, airborne, or surface based, underwater acoustic measurements relative to bottom points to link these measurements are essential.

Computation and Adjustment of Observations

Two examples of measurement and computation can be described. The first one involves the position of a ship relative to bottom geodetic markers. The problem of determining the surface-ship position relative to the underwater geodetic markers is similar to an intersection problem in geodesy in three dimensions. An arbitrary coordinate system can be established for these computations. The coordinates of the bottom markers are given as x_i, y_i, z_i, (i = 1, 2,

3). The distances, R_i, from the ship to the markers are measured by acoustic travel time. The unknown position, X, Y, Z, of the ship is determined by solving the intersection of three spherical surfaces in terms of x_i, y_i, z_i, and R_i. The availability of more than three bottom markers would give redundancy and permit adjustment.

The second example involves the computation of long lines forming a trilateration network. The measured distances must be computed using special formulas and reduced to ellipsoidal distances. These formulas have been developed and tested by others. The latest corrections to these formulas have been prepared by Thomas and applied for solving navigation problems [Thomas, 1965]. The methods of computation and adjustment of trilateration networks have been described by Ewing [1962] and others [De Loach, 1963] who used the method of variation of parameters. In this method the observed quantities are functions of the independent unknowns. Observation equations of the form $v = ax + by + cz - l$ for each line can be written where v is the residual error; a, b, c are coefficients to be determined by least squares; x, y, z are the unknown shifts, and l is the difference between observed and computed distances.

Differential formulas have been developed by Helmert for long lines relating variations in length with variation in geographic position of the terminal points of the geodesic line on the ellipsoid. The observation equation for a Shiran/Hiran line has also been developed. Observation equations for all lines can be written and the normal equations can be formed. The backward solution of the normal equations determines the unknown quantities and the forward solution gives quantities used in the error analysis. The whole adjustment process has also been developed to be performed on a computer using matrix algebra. It is only after solving for the unknowns and determining corrections to the observation of a given network that the final coordinates of the control points can be determined with certain accuracies.

MARINE GEODETIC RANGE

Some long-range navigation systems are currently employed in providing the geodetic control needed for deep-water operations. These sys-

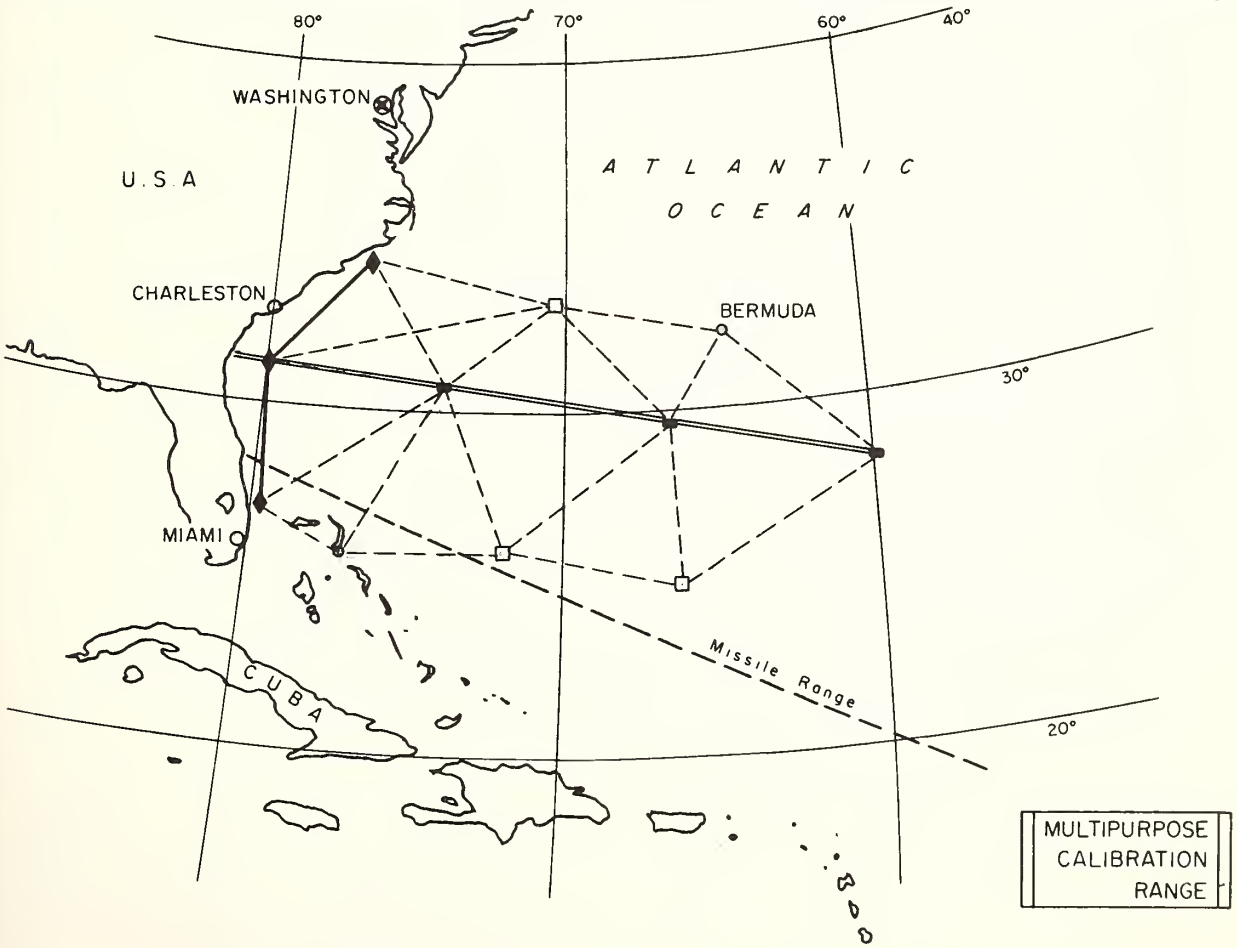

FIGURE 3.—Possible structure of a marine geodetic calibration range.

tems, and even the hundreds that are used in near and intermediate ranges, suffer in accuracy and reliability. Present limitations on accuracy arise, in part, because of the lack of reliable marine reference systems, including permanent geodetic marine control points. Positional fixes made with present systems at sea are often in error by one or several miles, depending on the area and the system used.

If a marine standard could be established at sea, navigation systems and, more important, surveying systems could be tested, calibrated, and evaluated. A marine, geodetic calibration range could be established using present techniques available to marine geodesy [Mourad and Frazier]. Figure 3 shows how such a range might be structured. The feasibility of such ranges is being analyzed. It appears that a range of high accuracy could be established. The range itself would be about 1,500 miles long, extending to sea and composed of several control points, both temporary and permanent types.

MARINE GRAVITY-BASE-STATION NETWORK

As mentioned earlier, the establishment of gravity-base stations in the open ocean to control airborne-based and surface-ship-based surveys is of primary importance. Figure 4 shows the necessary stations to cover most of the North Atlantic Ocean. These stations are spaced at 10° intervals or approximately one station at every 600 miles. Some of the indicated stations near shore are not necessary because of their proximity to land and possibly the availability of gravity control.

Gravity-base stations could serve as marine geodetic control points. At each base station surface-ship or submarine instruments could be employed to measure in detail the gravity over an area of perhaps 1° x 1° or 60 x 60 miles. At the control station, for a more precise base value, an underwater gravity instrument could be used. The end result would be a systematic network of detailed surveys over the oceans which could be used for airborne control.

Before such a program can be established, however, it is necessary that it be tested. For test purposes, the marine geodetic range stations could be used most effectively. The detail of the stations is even closer at 5°x 5° intervals. This way, we can kill two birds with one stone.

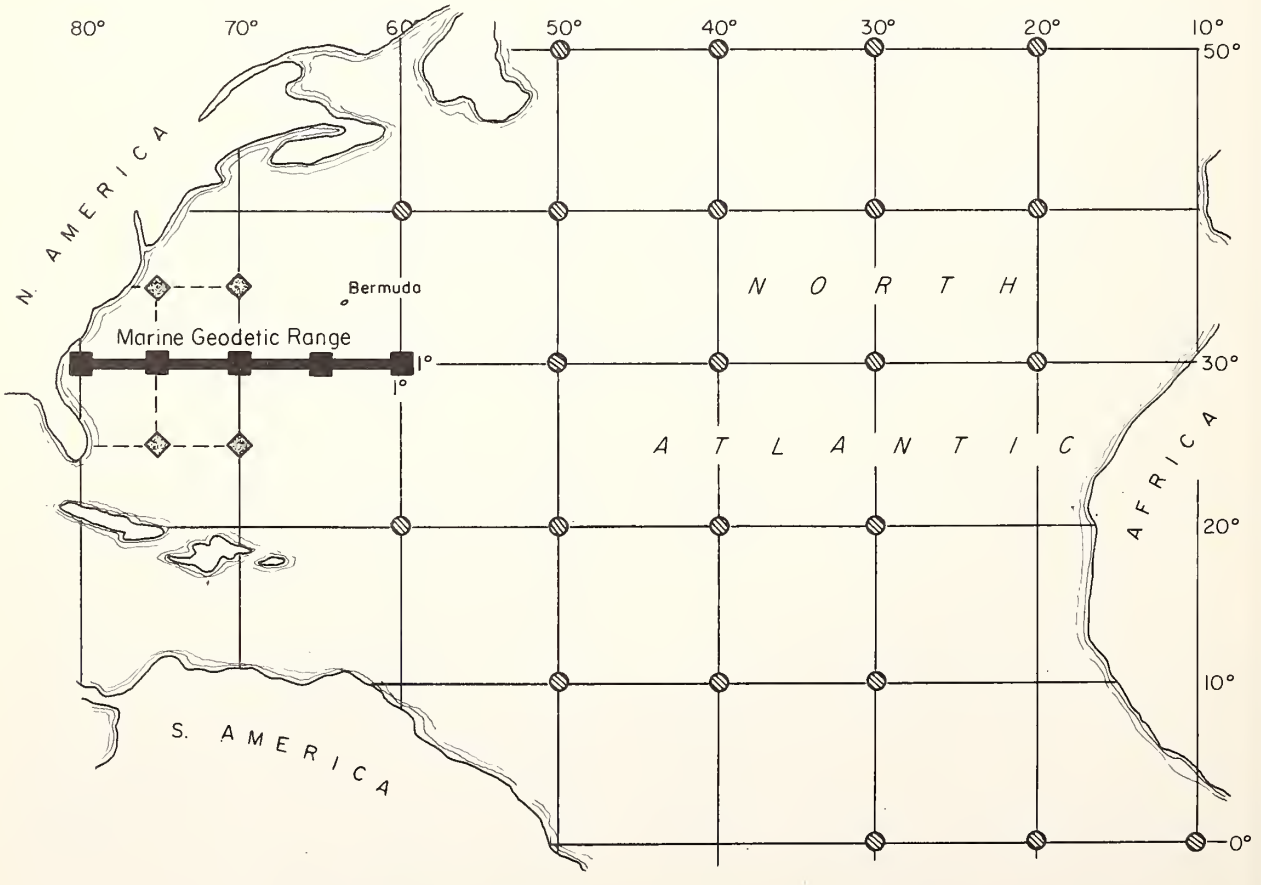

FIGURE 4.—Marine gravity base-station network.

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Relationship Between Marine Geodesy and Oceanographic Measurements

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ABSTRACT

The astronomical tide, the setup due to wind stress on the sea surface, the effects of changing barometric pressure and of regional differences in the vertical gradients of water density cause the physical sea surface to depart significantly from the geoid. The geoid would serve as an appropriate reference surface for oceanographic measurements if it could be established with sufficient accuracy at sea. Requirements are discussed together with some astrogeodetic and gravimetric measurements of the level-surface topography across short reaches of ocean.

According to G. Bomford [1962] the geoid is "that equipotential surface of the earth's gravitation and rotation which on the average coincides with mean sea-level in the open ocean." The fact that mean sea level is not, strictly speaking, an equipotential surface, owing to differences of water density in the oceans, the effects of prevailing winds and barometric pressure, and the like, is of importance to oceanographers. Even more interesting than these nearly steady influences are the time-dependent departures of the physical sea surface from the geoid.

For oceanographic purposes it is not the attitude of physical sea level that is of most importance, but rather the gravity potential of some standard isobaric surface. From the changes in the dynamic height of an isobaric surface with horizontal distance, it becomes possible to know the absolute field of horizontal gradients of pressure in the ocean, and from this in turn, to compute the field of motion in the sea [von Arx, 1962]. This is a problem to which the attention of oceanographers has been addressed for about a century [Defant, 1961]. The absolute transport [von Arx, 1965b] of mass, heat, and momentum by the oceans and the exchanges of these properties with the atmosphere and solid earth is of central concern in understanding the behavior of the earth's fluid layers. The time scales involved in these aspects of the oceanic circulations and levels can range from an instant to the geologic age of the earth.

OCEANOGRAPHIC DATUM

The suitability of the geoid as an oceanographic datum is evident. But the potential of the geoid cannot be measured directly, hence the geoidal surface must be traced from some standard origin and in some well-established coordinate system. Two are available: The geocentric system in which the earth is regarded as a true sphere, and the geographic system in which the earth is considered to be a perfect ellipsoid of revolution. To establish the geoid at sea, it would be necessary to measure the inclinations of gravity vertical with respect to geocentric vertical, or the deflections of gravity vertical with respect to normals to the spheroid. Geocentric coordinates have a desirable simplicity, but navigational satellites do not, in general, fly high enough to make the "point mass" assumption valid. Not enough is yet known of the mass distribution within the earth to allow suitably precise conversion of the direction of the apparent center of mass to the true center. Therefore, it seems best for the present to relate gravity vertical to the spheroid and measure deflections of vertical in the traditional sense.

It then remains to measure the departures of the physical sea surface from the geoid and to correct these measurements for atmospheric pressure so that the gravity potential of some arbitrary isobaric surface can be known at sea. This problem has been approached through the measurement of slopes, using the horizon as an indicator of the tilt of the physical sea surface with respect to gravity vertical.

GRAVITY VERTICAL

An inertio-optical system has been developed for sensing gravity vertical at sea. It consists of a Sperry Mark 19 Mod 3c meridian gyrocompass on which is mounted an equatorial theodolite for astronomical navigation, or alternatively a Kern DKM-3AX first order theodolite for measuring the tilt of the horizon. In the navigational mode the system bears the name GEON (Gyro Erected Optical Navigation system) and has the

FIGURE 1.—A Sperry Mark 19 Mod 3c meridian gyrocompass fitted with a Kern DKMO2 theodolite (modified by Perkin-Elmer) for celestial navigation. The R.A. drive motor is controlled by switches in the observer's left hand. His right hand holds a stopwatch. The low elevation of the polar axis indicates that the ship was near the equator. Star sights can be made in full daylight as well as at night with the GEON system. A single sight provides a fix of position.

present capability of finding gravity vertical with an accuracy of 0.15 arc-minute or astronomical position to 0.15 nautical mile (r.m.s.) under ordinary conditions of ship motion and maneuvering [von Arx, 1965a]. With the ship hove-to and a liquid mirror mounted on the phantom of the gyrocompass, reference to gravity vertical can be improved to the vicinity of 2 arc-seconds [von Arx, 1966a]. Much as this system improves the art of astronomical navigation at sea, it leaves much room for improvement in the practice of physical geodesy across oceans, or for the measurement of sea surface slopes.

High accuracy is required because the angles by which the regional sea surface departs from level are small (see table 1). There is also a problem in separating these effects.

TABLE I

Magnitudes of regional sea surface slopes produced by synoptic influences (angles in radians).

Equilibrium tidal slopes in midocean		10^{-10}
Wind setup in open ocean (Trades)		10^{-7}
Geostrophic slopes in middle latitudes for ordinary speeds of flow	1 cm/sec	10^{-7}
	10 cm/sec	10^{-6}
	100 cm/sec	10^{-5}
Shelf tides; Tsunamis in deep water		10^{-5}
Barometric loading:		
Margins of anticyclones		10^{-5}
Cores of extra-tropical cyclones		10^{-5}
Hurricanes (near eye)		10^{-4} to 10^{-3}
Wind setup by coastal gales		10^{-4}
Tidal slopes in embayments and canals		10^{-4}
Bores and surface waves		(not regional)

PHYSICAL SEA SURFACE

The surface of the sea departs from the geoid in four different modes; ***periodic departures*** associated with the gravitational influences of the sun and moon and the passage of waves of various kinds; ***synoptic departures*** produced by wind stress and synoptic and seasonal changes in the barometric pressure on the sea surface; ***climatological departures*** accompanying the climatological mean pressure distribution of the atmosphere and the density of the water at and below the sea surface; and ***secular departures*** occasioned by the slow rise of sea level with the melting of glaciers, the accretion of juvenile water from volcanoes, and modulations of the ocean-basin capacity dictated by crustal movements. These influences are separable by their frequencies.

Gravitational effects of the sun and moon produce inclinations of the physical sea surface that are long in period compared with the time required to occupy an oceanographic station and, moreover,

are of small magnitude in the open sea, approaching 10^{-10} radian. By contrast, ordinary gravity waves come and go in large numbers during an oceanographic station and therefore produce effects that are subject to averaging and statistical elimination. Long-period waves are generally ephemeral and, for present concerns, of negligible amplitude [Munk, 1962].

Synoptic influences, such as the inclinations of the physical sea surface owing to variations of atmospheric pressure with passing weather systems, can be sensed by barometer [Gissler, 1947] and corrections applied. But the effects of wind stress remain.

Except near coasts where setup may be pronounced, the stress of the mean wind should be balanced by an equilibrium slope of the isobaric surfaces in the ocean transverse to the average wind direction—a result of the Ekman transport. In a variable wind, the isobaric slope should vary barotropically, provided the change in wind velocity persists for as long as a few pendulum days to a week, depending on the latitude. Should the duration of the change in wind stress be even more extended, the initially barotropic response of the ocean stratification may be gradually transformed into the baroclinic mode; the method proposed should be capable of sensing this.

Climatological influences on the departure of physical sea level from the geoid, owing to anomalous distributions of sea-water density [Stommel, 1965], are grist for the oceanographic observer's mill and offer no unusual problems of measurement or analysis. But, in passing, the Ekman transport under wind fields associated with the climatological mean atmospheric pressure distribution can, in time, eliminate or even reverse Gissler's inverted barometer effect on sea level.

Finally, the secular departures of physical sea level from the reference geopotential may be considered too slow [Fairbridge, 1961; Lisitzin, 1963 to be of concern during any single oceanographic cruise or possibly any oceanographer's lifetime and may therefore be corrected, as warranted, in epochs of time.

In this connection, we are reminded by Fairbridge [1961] that Stille gave the names *geocratic* and *thallosocratic* to the periods of geologic history when lands were high and dominant or when the seas overspread them. Barring chemical reconstitution of the earth and assuming that isostatic compensation of its crustal materials becomes virtually complete in time, it can be shown that the geopotential of mean sea level is not greatly disturbed by orogenic events. Eustatic changes in sea level are major movements of the strand line on the flanks of all continental masses which, according to Bucher [1933], are essentially the result of changes in the vertical distance between the mean levels of the ocean floors and continental surfaces. Given a fixed ratio of land and sea area on the globe, it follows that eustatic changes in sea level, other than those of glacial pulsations, must not alter the geopotential of mean sea level nearly as much as might be supposed from geomorphological evidence.

In the end, then, we are mainly concerned with eliminating the effects of atmospheric pressure on the height of physical sea level; a problem far more easily solved than that of finding the geoid.

OCEANOGRAPHIC REQUIREMENTS

Last spring, deflections of the vertical were measured across the Puerto Rico Trench [von Arx, 1966b] by direct (astrogeodetic) and indirect (gravimetric) methods. The traverse was run from north to south along the 66.3° W. meridian, as shown on the accompanying chart (fig. 2).

The site of this experiment favors significant findings from cruise measurements in that the free-air gravity anomaly over Puerto Rico Trench is very pronounced, and its gradients very steep. Along the 66.5 W. meridian the free-air anomaly approaches -385 milligals, and the anomaly isopleths are strongly elongated in the east-west direction. Thus, meridional deflections of vertical in the order of 1 minute of arc or more are to be expected; a magnitude which places them within the range of astrogeodetic measurement using available methods of marine navigation. Moreover, the trade winds which sweep the area can be very steady at times and the ocean currents, which also affect ship management, are generally weak and predominantly zonal; i.e. east-west. All of these factors provide a unique setting for a single component experiment in which the differences between geodetic and astronomical latitude, can be compared with reasonable assurance that the zonal components of the deflection are small, and that the local gradients of free-air anomaly are predominantly meridional.

The resulting astrogeodetic arc (fig. 3) is an early, if not the first, attempt to make direct measurements of the figure of a portion of the earth at sea [von Arx, 1966b]. The accuracy attained is barely comparable with that achieved by Eratosthenes two millennia ago when he estimated the circumference of the earth.

The accuracies required for oceanographic purposes depend on the nature of the problem to be investigated. For example; a vertical uncertainty of a meter would be useful in studies of global sea level (call this Class A); 10 cm. would be valuable for tides and wind-driven setup (Class B); but 1 cm. or better is required for geostrophic calculations (Class C). The following approaches may be considered:

1. *Satellite geodesy* offers promise for problems of Class A in finding the geoid to a matter of a few meters on a scale commensurate with

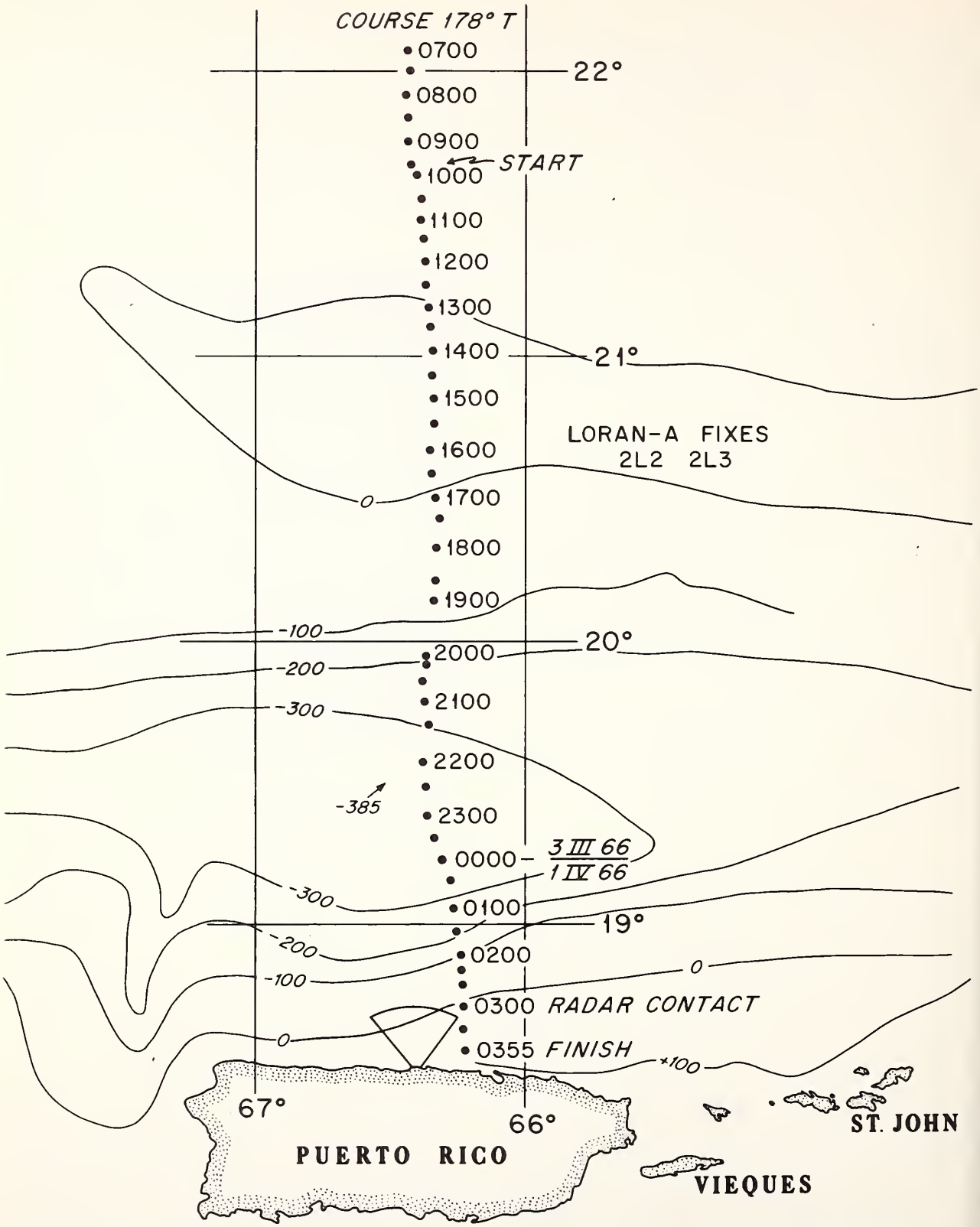

FIGURE 2.—Track of Research Vessel *Chain*, of the Woods Hole Oceanographic Institution, across the field of gravity anomalies over the Puerto Rico Trench.

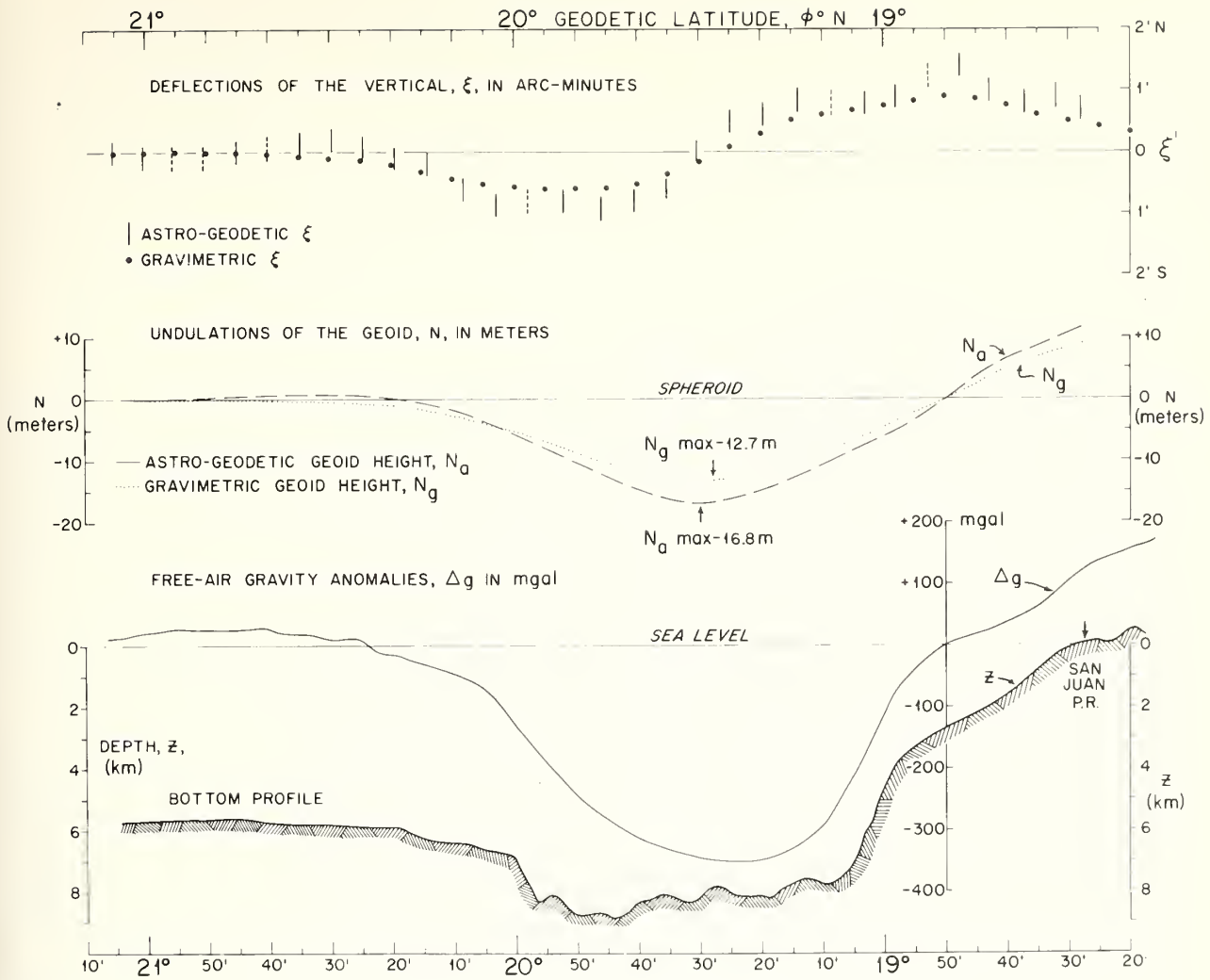

FIGURE 3.—*Top.* Measurements of the deflections of vertical across the Puerto Rico Trench. *Middle.* Curvatures of the geoid relative to the spheroid as derived from astrogeodetic and gravimetric measurements of the deflections of vertical. *Bottom.* Values of water depth and free-air anomaly observed along the Puerto Rico Trench traverse shown in figure 2.

the width of oceans. Spherical harmonic coefficients to order 8 have been evaluated by Kaula as early as 1959 and, since then, nearly twice that resolution has been attempted; but it is difficult to see how even a three-fold increase in resolution may be achieved because of the smoothing of the gravity potential at the height of the atmosphere above which satellites must fly. For this reason the potential applicability of satellite geodesy to problems of Class B is marginal and Class C highly questionable. Given sufficiently accurate orbital elements, however, and the vertical range from a satellite to the sea surface, alternative possibilities are offered.

2. *Gravimetry* with contemporary surface ship instruments offers a precision of about ±5 mgal under good conditions. This degree of uncertainty is mainly due to the error in Eötvös corrections for instrument pendulosity. With stabilized rather than pendulous support of sea gravimeters the need for the Browne correction vanishes. With improved navigational methods the Eötvös corrections may be specified to the point where, foreseeably, a shipboard gravimeter might be operated with a precision of ±0.5 mgal. Given gravity gradients to a precision of ±0.5 mgal a level surface could be traced with an error of height amounting to 10 cm. in 200 km. It should be noted that precision, not accuracy has been mentioned. The calibration drift of present-day sea gravimeters is such that standard stations must be visited every week or so for accurate results. Then too, for want of sufficient gravity data over the earth, it is still so difficult to use Stokes' theorem, that the practical calculation of deflections of vertical and of the corresponding figure of the geoid is subject to approximation and interpretive ambiguity. Even so, the gravimetric method has potentially sufficient precision to be useful in problems of Class B where leveling

is required across continental shelves or the open water stretches in island chains.

3. The *astrogeodetic* method requires two equally accurate systems of navigation—one giving position on the spheroid, and the other the direction of gravity projected to the celestial sphere. While modern developments in satellite and radio navigation are beginning to give geodetic position with adequate accuracy, there is still much room for improvement in celestial navigation. The latter requires clear skies, at least in the zenith, or the use of radio stars which in turn demands very large antennas or interferometer arrays which could not, even then, give usefully high angular resolution from shipboard. Present inertio-optical systems for astronomical navigation at sea are accurate to ±12 arc-seconds (r.m.s.) and can possibly be improved to ±1 arc-second [von Arx, 1966a]. But even with an accuracy of ±1 arc-second, an astrogeodetic traverse would lead to a leveling error of 10 cm in only 20 km , an order of magnitude coarser than that foreseeable for the gravimetric method.

Yet in face of these arguments, stands the fact that the astrogeodetic and gravimetric profiles across the Puerto Rico Trench have both described the geoid sufficiently well for the level-surface curves to regain the spheroid over the north wall with an error of closure of between 0.1 and 0.2 meter a run of 240 km. Compensating errors must have played a part, for the quality of each measurement could not otherwise warrant so favorable a result. This suggests that error analysis and statistical design would be a worthwhile guide in the further pursuit of techniques for leveling at sea.

In the statistical design of experiments, it may also be useful to consider a combined approach, in which the evidences of gravimetric, astrogeodetic and satellite observations are reconciled as in Kaula's [1961] description of the world geoid. The three approaches are supplementary. Surface ship gravity measurements tend to see details and lose accuracy with time (and distance), while satellite orbits reflect the low-order harmonics of the earth's gravity field. Astrogeodetic measurements at sea are relatively inaccurate but are, in principle, free of interpretative uncertainties, and are readily joined with the geodetic networks on continents. Through a balanced interplay of strengths and weaknesses the combined approach may offer unique advantages in further efforts to establish an equipotential datum for the oceans.

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The Law and Marine Geodesy

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The purpose of this discussion is to consider the relation of proposed marine geodetic systems to some of the present and prospective structure of the international law of the sea. Justification for this consideration arises from the fact that such systems will probably be installed in areas subject to varying kinds of authority by either the installing State or by some other State. Moreover installations in the sea, wherever placed in relation to national territory, may occasionally conflict with other activities in the vicinity. Should disputes arise in these situations international legal principles are likely to be invoked by those in controversy.

Mankind has benefitted from the ocean since time immemorial and laws regulating interaction on the ocean date back for many centuries. For the most part this international law of the sea developed as customary law rather than as consciously evolved and formally promulgated principles. In this century, however, more explicit and organized attention came to be devoted to the law of the sea and this eventually culminated in 1958 in a conference of 86 States in Geneva for the purpose of negotiating explicit agreements concerning much of this law. This conference produced four treaties or conventions, each dealing with a coherent aspect of the law of the sea: (1) the territorial sea and contiguous zone; (2) the continental shelf; (3) the high seas; and (4) conservation of living marine resources. All these treaties are now in effect between twenty-two or more States and the United States is a party to each of them. Although the principles of law within treaties are not binding as treaty obligations on any State not a party to them, at least two of the treaties—that on the territorial sea and contiguous zone and that on the high seas—are generally regarded as expressing customary international law. Hence these principles are binding on all States as part of customary international law. Another of these conventions, that on the continental shelf, also probably reflects customary international law in some important respects, but there may be disagreement about whether some of the detailed provisions of the convention are so generally accepted by States that they are a part of customary law.

Quite obviously only certain provisions of these treaties, or of customary law, have any relevance for the present discussion.[1] Before turning to a brief description of relevant principles, it is advisable to add a word of caution. By and large, the law of the sea evolved with respect to rather traditional uses of the ocean, such as navigation, fishing, and cable-laying, and there was little or no thought devoted to the many new activities and types of equipment now being undertaken, developed, or advocated. Hence it is necessary here, as is usually the case, to interpret inherited legal principles, if they are still useful at all, with new conditions and circumstances in mind so that modern needs are not thwarted by unwarrented extrapolation of older principles.

Within the limits of time now available, it is convenient to call brief attention only to one particular problem involving marine geodetic systems: the right, or lack therof, to emplace equipment within the territorial sea and other areas adjacent to particular States.

ACCESS

It is assumed that proposed marine geodetic systems must be distributed, sooner or later, over wide areas in the ocean. Efficiency of operation or maximum utilization of the system might thus require installations in some proximity to the coasts of States other than the installing State (the latter term is used to refer also to any group which may be identified with a particular political entity). The question posed is whether, in a particular area, the installing State

[1]Extended discussion of the law of the sea generally or even in specific relation to marine geodesy is obviously not within the present assignment. For more detail on the international law of the sea, without specific reference to marine geodesy, see McDougal and Burke, *The Public Order of the Oceans* (1962). Texts of the Geneva Conventions on the law of the sea, referred to in this paper, are appended to this book. For an extensive collection of national and international documents, official government statements, views of writers, and assorted memoranda, all bearing on the Geneva Conventions, see 4 Whiteman, *Digest of International Law* (1965).

may proceed without restriction from any political authority other than its own or whether the adjacent State may forbid or condition access in some way. This question can be examined in the context of various zones of authority generally recognized in the ocean: Internal waters, territorial sea, contiguous zones, continental shelf, and high seas. For this purpose, reference is made to preexisting law for each of these "zones."

A. Internal Waters

Probably little difficulty can be expected to arise with respect to internal waters which, generally, comprise areas immediately contiguous to land masses. Firstly, the need for oceanic bench marks may not be great here and, secondly, the legal position is very clear. Previous decisions fully establish that each State has full and complete control over virtually all activities within internal waters. Location of components of a geodetic system in these waters would, therefore, be dependent entirely upon the consent of the coastal State.[2]

On occasion this absolute authority in a coastal State could be exercised to interfere with an installation of some importance. While, normally, internal waters tend to be relatively restricted in size, there are certain special situations, noted more fully below, in which they cover a vast area. In such circumstances greater desirability could attach to emplacing geodetic equipment, but the measure of coastal authority remains the same.

B. Territorial Sea

The scope of State control over the marginal waters accepted as within the territorial sea is similarly well established. Generally speaking the coastal State has complete authority over the resources, fishery, and all others—including those of the seabed and subsoil of the territorial sea. Coastal authority over the access of foreign vessels and objects to the territorial sea is also wide, but not unlimited. Foreign vessels have a right of innocent passage, which is understood to mean that vessels are normally entitled to pass through the territorial sea so long as the passage is not "prejudicial to the peace, good order, or security of the coastal State." The wide range of coastal interests which might be subsumed under such terms of high-level generality as "peace, good order, and security" assures the coastal State of ample, but not unlimited, authority to protect legitimate interests. In addition the "coastal State may, without discrimination amongst foreign ships, suspend temporarily in specified areas of its territorial sea the innocent passage of foreign ships if such suspension is essential for the protection of its security." Suspension cannot be made effective until after publication.

There would appear to be little doubt that a coastal State may exert complete control over the use of the floor underlying its territorial sea. Unless such control were recognized, the coastal State would be unable to meet its responsibility for assuring the safety of navigation through this belt. Additionally, of course, a nonrestricted right to emplace equipment on the seabed within the territorial sea could limit the otherwise acknowledged coastal authority over the resources of the area. In short, access for this purpose would appear to be subject to the discretion of the coastal State.

C. The Limit of Internal Waters

As noted above, there may be certain instances in which geodetic equipment could be usefully deployed even in internal waters, as when the latter zone becomes larger. For this reason, principles governing water boundary delimitation are relevant considerations here. Traditionally, the areas denominated as internal waters were limited, but recent decisions have opened the way to inclusion of rather large expanses of the ocean. It is now generally regarded as permissible completely to include certain indentations into the coast, if the width of the opening does not exceed 24 miles in length, and if the opening is wider, the coastal State may then draw a baseline at the first place the indentation narrows to 24 miles. The effect of placing the baseline farther from the shore is to enlarge the area of internal waters, to extend the limit of the territorial sea and contiguous zones farther out from the coast, and to affect the limit of the continental shelf in some situations.

In certain conditions of water-land conformation, the coastal State may employ a straight baseline system, using, isolated bits of rock and islands offshore as points on the line. The general situation contemplated is described in Article 4(1) of the Convention on the Territorial Sea and Contiguous Zone:

"In localities where the coastline is deeply indented and cut into, or if there is a fringe of islands along the coast in its immediate vicinity, the method of straight baselines joining appropriate points may be employed in drawing the baseline from which the territorial sea is measured."

The first application of this system, which preceded its inclusion in the Convention, occurred in Norway and, when challenged, was supported by the International Court as conforming with international law. Subsequently the Convention included the above provision and it promises to

[2]It is useful to note, however, that problems of national law could be presented, since there are very frequently overlapping, and sometimes conflicting, controls and responsibilities within national, regional, and local agencies.

furnish the basis for sometimes marked extensions of internal waters. As is probably evident the use of this system can have considerable impact on foreign fishing activities in near-coastal areas, and in certain instances involving geodetic systems the system of baseline delimitation adopted by coastal States could be important. What may appear to be areas of high seas could turn out to be entirely within the claimed territory of an adjacent State.

D. Limit of Territorial Sea

Since the boundary of the territorial sea represents the outer limit of a state's most comprehensive authority, sometimes called sovereignty, the location of this boundary might have effects upon marine geodetic activities. The present international position on this problem is therefore relevant. This issue was one of two left unresolved at the 1958 Geneva Conference on the law of the sea and again at a 1960 Conference called especially to deal with this issue. Hence the new convention on the territorial sea has nothing to say on this key issue and even now it is necessary to be tentative in identifying a general consensus among States on the permissible breadth of the territorial sea. The United States position, the one we claim for ourselves and urge on others, is that 3 miles is the only limit universally agreed as permitted by international law. At the same time there appears to be a pattern emerging which may, perhaps sooner than later, indicate general, if tacit, agreement that a 6-mile territorial sea is permissible. There are, however, a number of States which claim a 12-mile territorial sea and a very few claim an even wider limit. In nearly universal opinion the latter claims are contrary to international law.

Whether the general community of States eventually agrees on a 6- or a 12-mile limit probably does not mean too much for marine geodetic activities in general, but the difference could in specific circumstances contribute special problems to the sponsors and installers of such systems.

E. Contiguous Zones for Special Purposes

The authority of a State over its nationals and over aliens does not end at the state boundary. In the case of its nationals a State may, if it wishes, extend the reach of its laws around the globe. This is quite familiar in the context of the ocean in particular. For aliens the situation differs, but here too a State may assert some authority to regulate the activities of aliens without its borders. In the present context one form of such regulation involves the extension of certain coastal laws to waters contiguous to its territorial sea; these are the so-called contiguous zones in which the adjacent state may exercise authority for special and limited purposes. It is important to note in this context that the recent Convention on the Territorial Sea and Contiguous Zone makes provision for the latter in terms which are clearly restrictive of coastal protection. Article 24 states that "1. In a zone of the high seas contiguous to its territorial sea, the coastal State may exercise the control necessary to: *(a)* Prevent infringement of its customs, fiscal, immigration or sanitary regulations within its territory or territorial sea; *(b)* Punish infringement of the above regulations committed within its territory or territorial sea. . . ." As far as a coastal State relies on Article 24 to support any extension of legislation into a contiguous zone it would seem that only "sanitary" regulations could reach activities in installing and maintaining a marine geodetic system. In particular, should such a system depend upon a nuclear power source, a coastal State might contend that its interest in freedom from potential pollution warrants extension of certain of its laws. With exercise of reasonableness and good faith in compliance with such laws, assuming they were warranted in the first place, there should be no impediment to development of marine geodetic systems on this account.

To complicate this discussion a bit, note that Article 24 makes no reference at all to any coastal interest in its security and defense. This is not because States cannot legally act in contiguous zones for these purposes, merely that such action is fully recognized in customary international law under proper circumstances, without the limitations imposed by Article 24. Hence it is important to ask whether States can legitimately perceive the installation of components of a marine geodetic system in contiguous waters as in some way prejudicial to national security. Given the numerous different political systems, beliefs and adherences now and in the future, it appears likely that some States will apprehend this relationship. It is not intended here to seek to resolve this problem, if in fact it can be. There is no question, I assume, that these systems will serve military purposes as well as others, even though these military purposes do not at all involve direct action against anybody, including the adjacent State or States. Presumably these systems would lend efficiency to other military operations and measures, however, and this could be regarded as inimical by the adjacent State to its general military and political position. Nonetheless to me, at least, these considerations alone do not seem to warrant the conclusion that an adjacent State could lawfully exclude the system from adjacent waters beyond its territorial sea.

In this connection the general objectives sought by developing and using marine geodetic systems

are of special importance since the conception of objectives affects the degree to which the systems serve the common interests of States generally. The greater the degree of general usefulness of these systems, in the sense that States, and private groups, generally derive concrete benefits, direct and indirect, the easier it is to defend the system, and activities associated with it, as falling within the general principle of full use of the high seas beyond the territory of particular States. Unless a State can demonstrate that the emplacement of such a system has direct, undesirable impact upon its exclusive interests, defined in terms of specific social processes operative within its territory, it should not be permitted to invoke international law in justification of interference with the system or its installation.

F. The Continental Shelf

Probably the ocean floor region denominated as the continental shelf, and especially defined for legal purposes, is of most concern for the present discussion. One of the Conventions emerging from the Geneva Conference of 1958 concerned this area and mention must be made of certain provisions therein. In addition recent national legislation in the Netherlands suggests the possibility of certain developments in customary international law regarding this area which are relevant here.

The following discussion examines, first, three aspects of the Shelf Convention and, second, possible evolution in customary international law of the shelf.

(1) Coastal Authority Over the Continental Shelf

Convention Article 2(1) provides:

"The coastal State exercises over the continental shelf sovereign rights for the purpose of exploring it and exploiting its natural resources." Perhaps the most important observation to be made about this provision for present purposes is that, contrary to some apparently informed opinion, it does not sanction the inclusion of the continental shelf (as defined in the Convention) as part of national territory. What it does accomplish is to establish that the coastal State has "sovereign rights" over the shelf for assuring exploration, and exploitation, of the natural resources to be found there. The competence thus conferred is not all-embracing and, in particular, it does not appear to include the full range of the legislative authority of the coastal State. This means that coastal States are not free, at will, to interfere with all activities on the shelf. Certain more specific provisions regarding other activities are discussed below.

(2) The Limit of the Continental Shelf

Should legal questions arise over installing geodetic systems in "shelf" areas, the region included therein is of obvious concern. It is generally understood that the legal definition of the shelf in the 1958 Convention does not coincide with the usual geological conception. Article 1 describes the shelf as ". . . the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas; . . ." The former of these two criteria is, indeed, often accepted as the conventional definition of the shelf, but as is known this is only a very rough approximation. In any event, and speaking generally, wherever the 200-meter contour line may fall on the floor of the sea adjacent to a mainland or island coast the area within it is considered to be the shelf for the purposes of the Convention.

As may be seen, the definition, in its second part, is open-ended, depending upon the development of the technology of exploitation. While no one can now say where the shelf ends, so far as the legal formulation is concerned, there are a number of reasons for concluding that this arrangement was not intended to serve as the means for dividing up the floor of the entire ocean among "coastal States." Obviously this interpretation by no means dispels the uncertainty about where coastal authority over the shelf ends and the region of free sea, and sea floor, begins.

(3) Accommodating Conflicting Uses of the Shelf

The Convention makes very general provision for the problem, widely preceived before the Conference convened, of accommodating oil exploitation with other activities. Insofar as geodetic systems would be emplaced only within the water column and not on the ocean floor, Article 3 is significant. It provides:

"The rights of the coastal State over the continental shelf do not affect the legal status of the superjacent waters as high seas, or that of the airspace above those waters."

This means that in these waters activities are protected by the general doctrine of freedom of the seas, which is defined in Article 2 of the Convention on the High Seas. After enumerating the freedoms to navigate, fish, and fly, and lay submarine cables and pipelines, the Article continues: "These freedoms, and others which are recognized by the general principles of international law, shall be exercised by all States with reasonable regard to the interests of other States in their exercise of the freedom of the

high seas." Without going into detail it is believed the installation and maintenance of a geodetic system, or components thereof, within the water colum is a use fully protected by this general reference to other freedoms. Access should only be limited by the consideration of reasonable regard for other uses. If little or no interference with other uses is likely, no difficulty should arise. It may be noted, however, that in the contiguous zones mentioned above other factors may have to be considered. There are otherwise, however, strong legal arguments to be invoked in protecting installation of these systems.

With regard to emplacement on the shelf, other provisions are pertinent, especially Article 5(1) and 5(8):

"1. The exploration of the continental shelf and the exploitation of its natural resources must not result in any unjustifiable interference with navigation, fishing or the conservation of the living resources of the sea, nor result in any interference with fundamental oceanographic or other scientific research carried out with the intention of open publication."

"8. The consent of the coastal State shall be obtained in respect of any research concerning the continental shelf and undertaken there. Nevertheless, the coastal State shall not normally withhold its consent if the request is submitted by a qualified institution with a view to purely scientific research into the physical or biological characteristics of the continental shelf, subject to the proviso that the coastal State shall have the right, if it so desires, to participate or to be represented in the research, and that in any event the results shall be published."

The question posed by these provisions is whether or not installation of a geodetic system is comprehended by the terms used. Certainly, these systems are not "navigation" although they are designed to make substantial contribution to this use of the sea, nor can they sensibly be called "fishing" or "conservation." Again, these stations may be used for scientific research into oceanic phenomena, but they also serve other purposes of an operational character. If such stations were regarded as useful for research into the shelf itself, in contrast to fundamental research generally, the provisions of Article 5(8) would seem to be especially pertinent for this envisages the necessity for obtaining the consent of the coastal State, a need which might very well discourage geodetic work of this kind in certain instances.

It is not necessary, nor is this writer competent to suggest, definitive answers to the problem that could arise in this connection. Considering, however, the general value of marine geodetic systems for many quite important ocean uses, every effort should be made to protect them against interference by coastal States. It is quite clear that this type of installation was not within the specific contemplation of the framers of this Convention. It is wise policy to preserve the ocean, and the floor thereof, for as many productive uses as possible which do not involve preclusion of other consequential activities. To the extent these systems do not so preclude or do so in minor degree, they should not fall within the scope of coastal control over shelf installations.

4. Developments in Customary Law

Recently the Netherlands promulgated legislation entitled the North Sea Installation Act of 1964. In a recent study of this act the authors assure us that it is not based upon the Continental Shelf Convention and that

"There is . . . every reason to conclude that the action taken was based upon a new rule of international law, which may be summarized as being that a coastal state may exercise jurisdiction over all installations erected on the soil of its continental shelf, no matter for what purpose."[3]

The authors predict that "there is no likelihood" that "the future practice of States might lead to a rejection of the alleged new rule."[4]

Should States generally, or even some key ones, adopt similar legislation applicable to all installations to be placed on the shelf, it would seem highly likely that the proposed marine geodetic systems could encounter difficulties. The relevent provisions of this legislation are as follows:

"Whereas we have deemed it desirable to make provision for the protection of legal interests in respect of installations on the bed of that part of the North Sea the boundaries of which correspond with those of that portion of the continental shelf which appertains to the Netherlands, until such time as the matter is regulated by international agreement;

"So We, having heard the views of the Council of State and with the advice and consent of the States-General, have approved and understood, and do approve and understand, the following:

'Section 1. In this Act the term 'sea installation' shall mean an installation erected outside territorial waters on the bed of that part of the North Sea the boundaries of which correspond with that portion of the continental shelf which appertains to the Netherlands.

'Section 2. The criminal law of the Netherlands shall apply to all such persons as commit any offense on a sea installation.

[3] H.F. van Panhuys and M.J. van Emde Boas, Legal Aspects of Pirate Broadcasting: A Dutch Approach, 60 *Am. J. Int'l. Law*, 303, 337 (1966).

[4] *Id.* at 338.

'*Section 3.* Provision may be made by Order in Council that any provisions of the statutory law of the Netherlands shall apply on and with respect to sea installations.

'*Section 4.* Provision may be made by Order in Council for the extension to sea installations of the jurisdiction of authorities and officials entrusted with the implementation of the provisions referred to in Section 3 above, or with the investigation and prosecution of offenses or with the bringing to trial of those responsible or with the execution of any sentences that may be passed by any court.

'*Section 5.* Provision may be made by Order in Council that the criminal law of the Netherlands and such statutory provisions as are referred to in Section 3 shall not apply to such sea installations as are described in such Order in Council or shall apply to such installations only to a limited extent.

'*Section 6.* If, within three months of the coming into force of an Order in Council, issued in terms of Section 3 or Section 5 above, We have not had a bill laid before the States-General to replace such Order in Council, or if such bill is withdrawn or defeated, We shall without delay repeal such Order in Council.

'*Section 7.* Regulations may be made by Order in Council in respect of installations erected or to be erected outside territorial waters on the bed of that part of the North Sea referred to in Section 1, in the interests of shipping, the fishing industry, the conservation of the living resources of the sea, pure scientific research, the laying and maintenance of submarine cables and pipelines, and the prevention of the pollution of the sea, as well as for the protection of such other interests as are recognized by international law.

'*Section 8.* Any contravention of regulations made under Section 7 shall be punishable by a fine not exceeding ten thousand guilders. Such contravention shall be considered to be an "overtreding" [corresponding to the French *contravention*, i.e., a minor infringement of the criminal law.]' "

It is perhaps of interest to note that this extremely broad claim to jurisdiction and control came about because of the installation of a radio and television station (Radio—TV Noordzee) on a platform erected in the ocean beyond the territorial sea. The broadcasters into the Netherlands were illegal under Dutch law, if Dutch law extended to the stations and their broadcasts. This legislation provided a domestic law basis for taking action against them, which action was taken in combined helicopter—small boat foray by the police. This immediate occasion for legislation appeared to provide ample basis for coastal state action, since the station's sole purpose was to evade Dutch law, and it may turn out that the Act will have little impact upon legitimate activity offshore the Netherlands. However, the blanket provision for the extension of national law to any installation on the shelf could, both in this case and in others involving governments less concerned for free access to and use of the ocean floor than the Netherlands, be employed to inhibit and even prevent efficient use of this area. Certainly there would seem to be little doubt that legislation so broadly conceived and phrased would permit the extension of any provision national decision-makers chose to adopt, without regard to effects upon the use of the area. Nothing in this legislation suggests standards or criteria for determining what laws should extend to offshore installations and it seems to me rather obvious that officials in some state could, pursuant to identical legislation, harrass and perhaps completely frustrate legitimate scientific or other operations in the adjacent shelf-region. There should be no need to emphasize that marine geodetic operations which involve putting structures on the shelf could fall within the ambet of such legislation and could be detrimentally affected thereby.

Session I Panel Discussion

PANEL MEMBERS

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DISCUSSION

QUESTION FROM FLOOR: Mr. Chairman, I would like to ask some legal questions of Prof. Burke. You very adequately covered the discussion of international conventions. Would you comment about the salvage problem, for example, the recovery of a submerged buoy in deep water?

PROF. BURKE: You are asking the wrong man since this is a question of Admiralty Law and I do not know anything about it. Insofar as the law concerning buoys is applied beyond national territory, as I understand it, there is a considerable amount of work being done now through the Intergovernmental Oceanographic Commission in identifying problems. There has been one comparative study done with specific reference to buoys, but it is limited to American-British law. It was done at Ohio State University, but I cannot answer any questions about it.

QUESTION FROM FLOOR: I imagine that it is a question of what a fellow can get away with, find the buoy and take it?

PROF. BURKE: Well, I understand people have been getting away with some of them. This is an area, I understand, where very little has been done and something needs to be done very badly.

QUESTION FROM FLOOR: Professor, again on the question of law, has there been any opinion on the question of invasion of hydro-state by surface craft, or military craft, which does not touch bottom and does not do any operation other than exist as far as the coastal state is concerned? Does the coastal state exercise any authority?

PROF. BURKE: You mean beyond territorial sea?

REPLY FROM FLOOR: Beyond territorial sea.

PROF. BURKE: Over the continental shelf?

REPLY FROM FLOOR: Over and above the shelf.

PROF. BURKE: The way I would interpret the provision—Article 5A, on Coastal Authority—the authority is limited to those activities, specifically, directly, affecting the shelf and not the waters above. Now, I say I think that is the way to interpret it, to limit it, but I do not know whether it makes any sense whatsoever, in certain context, to try to make that kind of distinction. It seems to me that maybe the areas are not that disparate or distinct, that you can separate the certain water and research in the extended boundary area bottom. Extended boundary, I gather, includes the water too. And, so that authority of that Article appears to be limited to a certain kind of research. I am not at all sure that it will work out that way, in fact.

MR. GRIFFIN: I think it might be well to add to what Professor Burke said in his paper, pointing out that the convention, as an international treaty, gives to the signatory states so-called sovereign rights, whatever that means, over the exploitation of the natural resources of the shelf. And, the history of it shows that it was contemplated to mean less than a claim of territorial sovereignty. Nevertheless, the treaty, or no other treaty or international law, prohibits a state from claiming full, and exercising and asserting full, territorial sovereignty over its continental shelf. The Netherlands legislation is a step in that direction. The United States Outer Continental Shelf Act is a step in that direction. I think that the emplacement of geodetic instruments in the future, on the floor of the continental shelf, will have to face up to the need for reconciliation with this problem. Our own government is perhaps one of the earliest example setters, through our own legislation, of asserting--without using the various territorial sovereignty—the Outer Continental Shelf Act asserts jurisdiction and control in the United States in such broad sweeping terms, that it can be interpreted in practice and in effect to mean only nothing short of full territorial sovereignty. This means that if you wish to establish a geodetic control installation on the floor of the United States Continental Shelf, you have to get the control of the United States Government.

DR. WORZEL (Lamont Geological Observatory): On the question of the law of the sea, for legitimate, scientific activities on the continen-

tal shelves it says that normally this will be granted by the adjoining states. But, does it do anything to prevent this state from stalling indefinitely, if they will, to give this?

PROF. BURKE: There is no provision in there that would prevent this type of harassment, and, in fact, I would be greatly surprised if it had not already occurred. In fact, I was told on one occasion that a survey of ten European countries' continental shelves was discarded because it would take longer to get the consent than it would to do the survey. Instances of outright refusal of consent have occurred. Now, I do not know how many other instances there are of this type of delay—but, it is obvious that it could be used very easily for delay purposes and that it has a practical effect in preventing the work.

Incidentally, the United States, I believe, has again taken the lead on something that I think may be undesirable, but it may be difficult to make that judgment. This is, to the effect that, it is now a matter of customary law that consent of the coastal state for research is required. This means that every state, no matter whether they are a party to the convention or not, can require consent before you can do scientific work on the shelf. It also means— and I suppose this is why it was mentioned—that we can demand a requirement of consent from states which are not parties to the convention, though we are. In other words, it is a sort of trade-off.

MR MOURAD: I would like to ask what is the difference between hydrographic and bathymetric surveys? Is there a difference, or is it just a matter of a difference of depth? I have been searching everywhere and cannot find any clear definition of either type of survey. Do these surveys overlap each other? Perhaps some expert in the audience can give us some information.

DR. VON ARX: I will venture a guess as to what the distinction is. The bathymetric survey is directly interpreted as a sounding survey to find out how deep the water is. The hydrographic survey can be both; to measure either the depth of the water or the properties of the water. So, I think the words should be abandoned and, instead, use the word oceanographic survey. You have an oceanographic survey to study the water; you have a bathymetric survey to study the bottom; and a hydrographic survey to study something else.

MR. MOURAD: Would you refer to the maps as bathymetric maps?

DR. VON ARX: Bathymetric maps, why not. It is a clean word, might as well keep it clean.

DR. MORITZ: Are there any other questions or comments?

QUESTION FROM FLOOR: I have a question on the sharing of research that you do on the continental shelf and similar places. The way it was explained by Prof. Burke, it was clear that if you do any research at all in the disignated areas, you must divulge the results. Must I divulge the results to my competitor? Is this the law?

PROF. BURKE: Your competitor in what way? Are you talking now about. . .

REPLY FROM FLOOR: Well, I am with company .... Let me speak of....

PROF. BURKE: The idea was to prevent surreptitious exploration for resources under the guise of scientific research, at least that is what I understand the idea to have been. This might be a matter of an arrangement with the other state and they might have an interest in the results themselves, but not divulging it to others. This could also protect you.

DR. MORITZ: Ladies and gentlemen, I am most unhappy to have to interrupt this interesting discussion for lack of time.

Requirements and Views of DOD in Marine Geodesy

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Before getting started on the topic included in the title, I would like to talk to you about some administrative details, and to disclaim association with many programs, thereby severely limiting the scope of this discussion. The Department of Defense (DOD) is enormous and is composed of many agencies working in a multitude of distinct disciplines. These agencies find that their activities require a diverse input of geodetic information, some of which is readily available, but some of which must be measured for the particular project being undertaken. The requirements of these agencies are, in general, completely unpredictable, and generally not extensive. I make no claim of speaking for them or even knowing what they might be doing.

The requirements I plan to address are those that are stated in support of approved systems now in existence or currently being developed. First let us examine what is and what is not within the purview of the DOD geodetic community. Some of these remarks may seem too basic for a meeting of this sort, but I have encountered many instances wherein a basic misconception of the role of the DOD in scientific research exists.

The basic mission of the Department of Defense is, in the simplest terms, the protection of the United States. It is definitely not the sponsorship of unlimited research. Although a great deal of basic research is sponsored by the DOD, before a developmental program can be undertaken the project concerned must be tied to a specific mission objective of the DOD. Once this test is passed, we must determine the accuracy we absolutely require in order for the system to perform within the approved limits. In conventional surveying, if a person used first order techniques to lay out construction lines, it would be considered a waste of money. The same principle applies to the surveying activities of the DOD. If it is determined that a relative accuracy of ± 30 meters over a short distance fulfills all the requirements for a particular project, then there is no reason for using instruments and techniques that will give decimeter accuracy.

The DOD geodetic requirements are dictated by the defense needs of the nation. In the early days of our history, we were interested only in our relationships with the people within one state or even one community. With this limited range of interest, there was no need for geodetic control extending over vast areas. In particular, no requirements whatsoever existed for a world datum, and the only interest we had in gravity was insuring that pendulum clocks kept fairly good time. Our navigation requirements were no more severe, being dictated only by the ability to avoid rocks and shoals, and to make a landfall. Errors of 5 miles or more were completely acceptable.

As time passed our national awareness increased, and we became interested in geodetic systems of broader scope—for instance, the one datum covering all of the United States or North America. Still, the requirement for knowledge of gravity for geodetic purposes was at a minimum.

In the past few years our international awareness and our technological acumen have been increasing at a fantastic rate. We now realize the importance of an accurate gravitational field, world wide, to use in predicting the course of satellites or space probes, and the necessity of having all land masses described in a commo reference system. Since the description of the gravitational field is easiest in a center of mass system, it is only natural that we should adopt a world geodetic system for positional information which is also based on the center of mass of the earth, and thus have positional information compatible with force field information.

We find that, along with our new-found international awareness, we now take a deeper look at all problems facing us. At one time, we simplified problems by making certain assumtions about the consistancy of certain parameters. Now, with computer capability, we make more so-

phisticated solutions and let more parameters vary. A case in point, though outside the field of geodesy, is the optimum ship routing systems now used. Whereas one would decide on a given course based on average historical weather conditions, and then doggedly stick to that course despite the weather, we now consider the forecast weather in determining the route we follow. As weather conditions change, course changes are radioed to the vessel so that smooth sailing may be obtained. Although the distance steamed may be increased by this routing method, time enroute is decreased, and voyage repairs are decreased. Less obvious corollaries exist with respect to geodetic information. When we concentrate on improving the accuracy of those parameters which are easy to improve, we can make the same net gain in system accuracy with the greatest economy; however, we attempt never to exceed the basic system requirements that have been established if the cost is thereby increased. If a system in existence meets the requirements for accuracy of the DOD, and if we are not suffering under the hardship of overly severe accuracy requirements on any of the system parameters, there is no reason other than economy or efficiency of operation for changing either our techniques or instrumentation. Under these conditions, contractors are wasting their time in trying to interest us in new instrumentation. Although this approach is not scientific, it does save a great deal of the taxpayer's money.

The basic administrative misconception which exists throughout the scientific community is that the DOD, since it receives a large proportion of the federal monies, is the logical department to approach with any newly developed techniques or equipment, and that the DOD should use the most accurate and most sophisticated equipment available regardless of its legitimate requirements. Unless a developer can prove conclusively that his brain-child will meet our requirements whereas existing instrumentation or techniques do not, or unless he can prove that there will be a cost advantage in adopting his system, he should not waste his stockholder's money trying to persuade the DOD of the great benefit in changing systems. These remarks apply not only to marine geodesy, which has not yet been exploited fully, but to geodesy in general.

Having completed a discussion of the views of the DOD, let us now turn to some requirements. These requirements are stated as what might be expected to be required during the next decade, expressed in terms of the standard error.[1]

a. The positions of a few super-control points, with accuracies approaching ± 50 feet,

b. The positions of selected points on the major land masses with accuracies approaching ± 100 feet,

c. The deflection of the vertical at selected points on the major land masses to accuracies approaching ± 1 arc second,

d. Azimuth determination at selected points on the major land masses with accuracies approaching ± 1 arc second, and

e. The gravitational potential of the earth at an altitude of 1 megameter with accuracies approaching one part in ten million.

The first requirement is needed in order to infer the dimensions of the reference ellipsoid and to orient the major land masses only, whereas the second requirement is what would be expected for any arbitrarily chosen control point. Both of these refer to the three dimensional position.

In satisfying these requirements we could be wildly optimistic and contend that (a) and (b) can be derived from satellite observations supplemented by conventional triangulation, and that these positions, when supplemented by astronomical observations, would then produce the desired information on the deflection of the vertical. Once the deflections were obtained, astronomical observations would then provide all the information needed to satisfy the requirements on azimuth, so all problems other than the gravitational field would be solved. The desired accuracies are not unreasonably severe, so this approach should be completely valid. We prefer, however, to be pessimistic with respect to too much reliance on statistical methods and to obtain a check on the satellite derived information. In order to provide this check, we will require a knowledge of gravity to guarantee the proper orientation of the major geodetic systems correctly in a world datum, we will then rely more on satellite methods to determine the locations of smaller land masses. The knowledge of gravity that is required for the datum orientation cannot be limited to land areas, but must extend to the ocean areas of the world surrounding each major geodetic datum.

So far we have considered geodetic requirements in land areas which require a knowledge of gravity in the marine environment. Let us now consider a problem more intimately connected with the oceans. In keeping with the nation's greater international awareness, the need has developed to maintain knowledge of the location of major fleet units on a continuing basis in the same coordinate system used for the land areas. Of course we do not expect geodetic accuracy for a moving platform in the middle of the ocean. This would violate our principle of obtaining data only good enough to satisfy our requirements. We are satisfied with high quality navigational control, but this in turn requires information of

[1] Appendix to minutes of the Second meeting of the NASA/DOC/DOD Geodetic Satellite Policy Board, 24 July 1963.

geodetic accuracy either on or contiguous to the ocean areas. Unfortunately, I am unable to address the positional accuracies required, but there are many considerations that may be discussed at this time.

The most popular positioning systems in use today for navigational purposes are the long-range electronic systems such as Loran. If we consider the installation of stations in a major datum that can be converted to a world geodetic system, and if we assume that trivia such as errors in the propagation velocity are nonexistent, then we can expect relatively high accuracy in the determination of positions at sea; however, we must keep in mind that these systems have hyperbolic lines of position, and that the expansion of the lanes as we depart from the baselines has an adverse effect on the resolution of the system. We must also keep in mind the angle of intersection of the two lines of position and use the system only in those areas where the position can be determined with reasonable validity. As the area in which the vessel is operating changes, it is necessary to change the location of the shore navigation stations used, or to accept some degradation in the positioning information. As we go farther out into the ocean, the problem becomes more acute. When we reach an operating area where it is necessary to select three islands for transmitting sites, we are severely limited in the configuration of the net. To further complicate the problem, those islands which are strategically placed for a given navigation net may not be diplomatically accessible for the construction and operation of navigational aids, so it becomes necessary either to use poorly placed transmitter sites or to move operating areas to locations where coverage by the long-range systems is sufficiently accurate.

Because of these limitations on the long-range electronic systems, especially when coupled with other problems such as uncertainties in the velocity of propagation, jamming possibilities, poor reception characteristics under many atmospheric conditions and a myriad of other features, other systems have been developed or are currently under development which are considered to be more universally acceptable.

The second system to be considered will be bottom contour navigation. The U.S. Navy has been quite successful in recovering positions at sea by matching fathograms taken over bathymetric features with the results obtained by a survey vessel whose position was accurately known. Although the recovery of position is considered good, we are confronted with the problem of how accurate the position of the survey ship was at the time it obtained the original survey data. This then breaks down, in most instances, to the problem considered before with the use of the long-range electronic systems, but with the added degradation caused by the additional sounding operations involved. There is one advantage over straight navigation by the long-range systems since the survey vessel could secure operations whenever the reliability of the positioning system was suspect and resume again when there was no question as to the validity of the data.

Navigation by geophysical phenomena has often been mentioned as a prospective device, with either lines of magnetic intensity or lines of the force of gravity being used. Since both of these systems are subject to a zero error, the relative intensitites along a given track are used rather than absolute values. Both of these quantities are convenient to use in that they can be sampled without any transmissions from the navigating vessel; however, they suffer from the same problems as the bottom contour navigation, plus the additional difficulty that resolution is not so good, under the present state of the art, as in the case of bottom contour navigation.

Navigation by satellite has become possible operationally during the last few years. The Navy Navigation Satellite System will be discussed by Dr. Robert Newton during Session V of this symposium, so I shall not attempt to do so here. For this part of the symposium, we will mention only that it is necessary to predict the position of the satellite accurately for about 24 hours from the time the last tracking data are received in order that the system may be used. The requirement for the gravitational field at an altitude of 1 megameter is in support of this system. If we were dependent on the knowledge of the gravitational field that could be deduced from our present knowledge of gravity anomalies, the system would be unusable. An extremely accurate description of the gravitational field at the altitude of the satellites is required. It is indeed fortunate that this field could be derived to sufficient accuracy at that altitude from satellite tracking data and did not need to be determined from terrestrial measurements. It is regrettable that we are unable to describe the same gravitational field at zero elevation to the same accuracy. Although this system provides measurement precision of geodetic quality, and has satisfied many of our geodetic positioning requirements, it must be borne in mind that the navigational data derived are not continuous, so some means must be available to bridge between fixes. The dynamics of the satellite system causes fixes in low latitudes to be about 2 hours apart.

This quite naturally leads us to the inertial system, which is the last system to be considered. The mechanical basis of the systems are such that the navigators attempt to track the local vertical rather than the geodetic position. If there

were no factors such as gyro drift to degrade the position keeping qualities of these instruments, they would do an outstanding job of indicating the astronomic position of the navigating unit; however, since there are errors which creep into the system, it is necessary to reset the navigator periodically. The combination of navigational satellite and inertial navigator should approach an ideal system. Unfortunately, when the inertial navigator is reset to the true position, the component of the gravity vector perpendicular to the ellipsoidal normal causes an apparent horizontal acceleration. This results in an oscillation of the nagivated position about the astronomic position with the Schuler period, with the plane of the apparent motion rotating about the astronomic position with the period of a Foucault pendulum. In areas where the deflection of the vertical is negligible, this is no problem; however, where the deflection reaches an appreciable mangitude, it is necessary to reset the inertial navigator to the astronomic position, and to correct positions indicated by the navigator for the deflection of the vertical in order to obtain an accurate geographic position. This requires a dense gravimetric survey of the entire operating area and areas immediately contiguous thereto, with the density of observations diminishing away from the area of interest.

Although a complete gravimetric survey is indicated as being essential, the density of observations required can be determined only after a preliminary investigation indicates the degree of gravimetric smoothness.

In this discussion of navigation systems, I have completely ignored error sources other than geodetic, considering those to be without the purview of this symposium; however, let us keep in mind the fact that error sources do exist, and that the errors are significant. Other disciplines are concentrating on their identification and elimination or compensation.

If we summarize the requirements mentioned above to support navigational systems, even though I have been unable to give exact figures for accuracies required at sea, it can be seen that the Department of Defense has a requirement for the same type of geodetic information in the 70 percent of the earth constituting the marine areas as it has in the 30 percent constituting the land. There is an immediate requirement for detailed gravimetric surveys in the northern hemisphere, with the elimination of holiday areas in the southern hemisphere, and for the precise positioning of transmitter sites for navigational aids throughout the ocean areas.

Marine Geodetic Problems of Industry and Commerce

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Geophysical Service, Inc., Science Services Division
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Many forward-looking scientists were involved in the formulation of this, the first marine geodesy symposium. These people have recognized the need for expansion of an old land-based technology, geodesy, into the marine environment. They have put together an excellent program covering the role marine geodesy will play in the developments of the future. I especially like the theme of problems, technologies and motivations because the challenge is presented, the technologies available are analyzed, and the motivation to expand the technology to meet the challenge is provided.

Industry and commerce have many uses for marine geodesy so I have a rather broad subject to discuss in a relatively short time. It is fortunate, however, that there are a relatively few basic geodetic problems that are common to all phases of industry and commerce.

A first requirement of marine geodesy is to achieve worldwide geodetic coverage to act as a base for the establishment of precise positions for mapping and precise knowledge of the earth's gravity field (fig. 1).

Achievement of this first requirement is vital to national defense because the effectiveness of sophisticated weaponry is dependent upon the precise positioning knowledge supplied by geodesy.

Development of marine resources, through the exploration, development, and exploitation phases, is dependent upon position-fixing.

Navigation, above and beneath as well as upon the sea, was the first use of geodesy. However, with expansion of commerce and development of marine resources by industry, navigation becomes more of a science and less of an art.

The installation of resource development platforms and accompanying increase in sea traffic places a new requirement upon geodesy. The safety and economy of these ocean environment activities becomes an important concern, related to navigation and position-fixing.

The scientific investigation of marine phenomena becomes more meaningful if the locations of the measurements are accurately known.

If we analyze each of these general applications of marine geodesy, we recognize a common basic requirement. This is position-fixing. This can be static or dynamic or both static and dynamic. Every oceanic activity has a static position-fixing requirement—of knowing precisely where on the face of the earth the activity is located. Most activities have a dynamic position-fixing requirement—of knowing precisely the location of one point of activity relative to adjacent points. This is an especially critical requirement in the case of exploration for resources and collection of scientific data (fig. 2).

As an example of the problems involving marine geodesy, let us examine the seismic method of exploration for petroleum. In this system a seismic detector hydrophone streamer as long as eight thousand feet is towed behind a vessel at a speed of 4 to 8 knots. An acoustic impulse is generated by a seismic source such as dynamite or a gas gun. The source may be located on the towing vessel or on a shooting ship. In the case of dynamite, a one hundred pound charge may be detonated every 45 seconds.

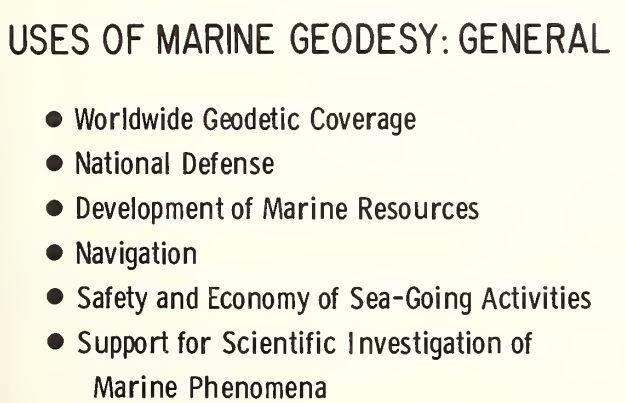
USES OF MARINE GEODESY: GENERAL
Worldwide Geodetic Coverage
National Defense
Development of Marine Resources
Navigation
Safety and Economy of Sea-Going Activities
Support for Scientific Investigation of Marine Phenomena

FIGURE 1.—Marine geodesy is an important contributor in expansion of oceanic activities.

BASIC GEODETIC PROBLEM; INDUSTRY AND COMMERCE

Position Fixing:

- Geodetic Location - Static
- Relative Position - Dynamic

Continuous Fixing
Distance - Velocity
Direction - Heading

FIGURE 2.—A primary need of industry and commerce in oceanic activities is position-fixing.

If a non-dynamite source such as several gas guns is used, a seismic record is obtained every six seconds. In this example, it is common practice to work 24 hours each day and more than 100 miles of subsurface profiling will be obtained (figs. 3 and 4).

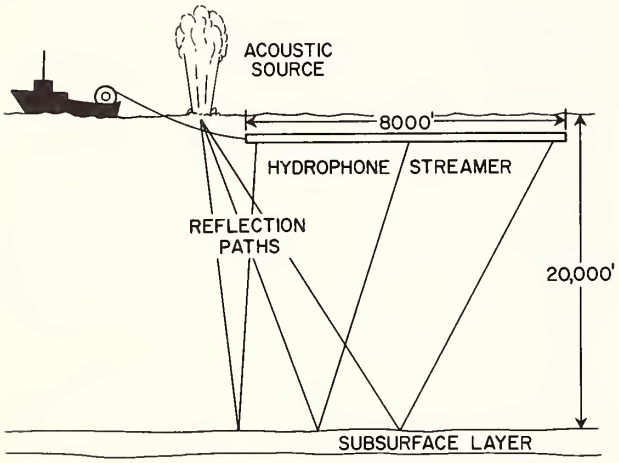

FIGURE 3.—The seismic reflection method used in exploration for petroleum requires accurate position-fixing.

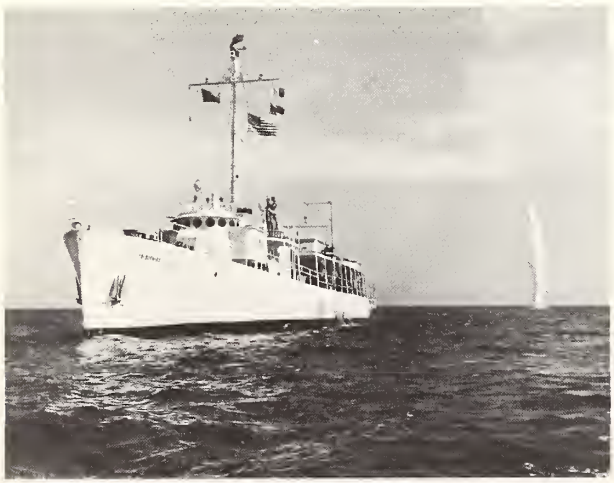

FIGURE 4.—Depth charge, dropped from survey vessel, generates acoustic impulse during seismic exploration at sea. More than 120 vessels of this type were used in seismic offshore exploration, worldwide, in 1966.

More than fifty vessels of the type illustrated have been operated this year by Geophysical Service Inc., in offshore waters ranging from Bristol Bay north of the Aleutians to the Bass Straits between Australia and Tasmania. To indicate the magnitude of offshore seismic exploration for petroleum, there were probably more than 120 ships engaged in seismic exploration in the free world during 1966.

A better understanding of the seismic problem is obtained by examination of a seismic subsurface section obtained in south Louisiana offshore waters. This section, nine miles long, obtained by digitally processing a sequence of 100-pound dynamite shots, shows the subsurface to a depth greater than 20,000 feet. The shot points, 300 feet apart, are shown along the top edge and the subsurface penetration in seconds is shown along the left edge (fig. 5).

The geologic interpretation of this subsurface seismic section depicts a salt dome surrounded by a shale mass. The sediments across the top of the dome are faulted in a typical graben pattern. Deeper sediments pinch out at the domal interface (fig. 6).

The seismic exploration program proceeds along a grid of lines covering the prospect area. These lines are chosen according to prior geological information. Seismic stations are located along each line at intervals ranging from 40 to 1,500 feet, depending upon the exploration objective and the method used. Thus, two requirements exist—the need to locate the line with an accuracy of 500 feet or better, and to place the stations along the line with an accuracy of 20 to 50 feet, relative to each other. In this discussion, accuracy is defined, using the conventional circular probable error (CEP) concept, to mean that statistically 95 percent of the readings would fall within a circle whose radius is the accuracy indicated (fig. 7).

Essentially all marine seismic work to date has been done at ranges less than 200 miles from shore. However, this activity is moving out into deeper water and work will be done in areas 400 miles from shore. Actually, the required accuracies have not been achieved at the 200-mile range in many instances, due to poor strength of figure, radio propagation effects, and low transmission power.

Seismic work, using dynamite as the acoustic source, has been limited to daytime operation. With the advent of new sources, such as the gas gun, it is now possible to work 24 hours per day. Thus, the positioning facility must have an all-weather, 100 percent utilization capability.

Additional performance requirements can be enumerated. One of the most important of these is system reliability. The mean time between failure (MTBF) must be high and the maintenance time (MT) and repair time must be low. With

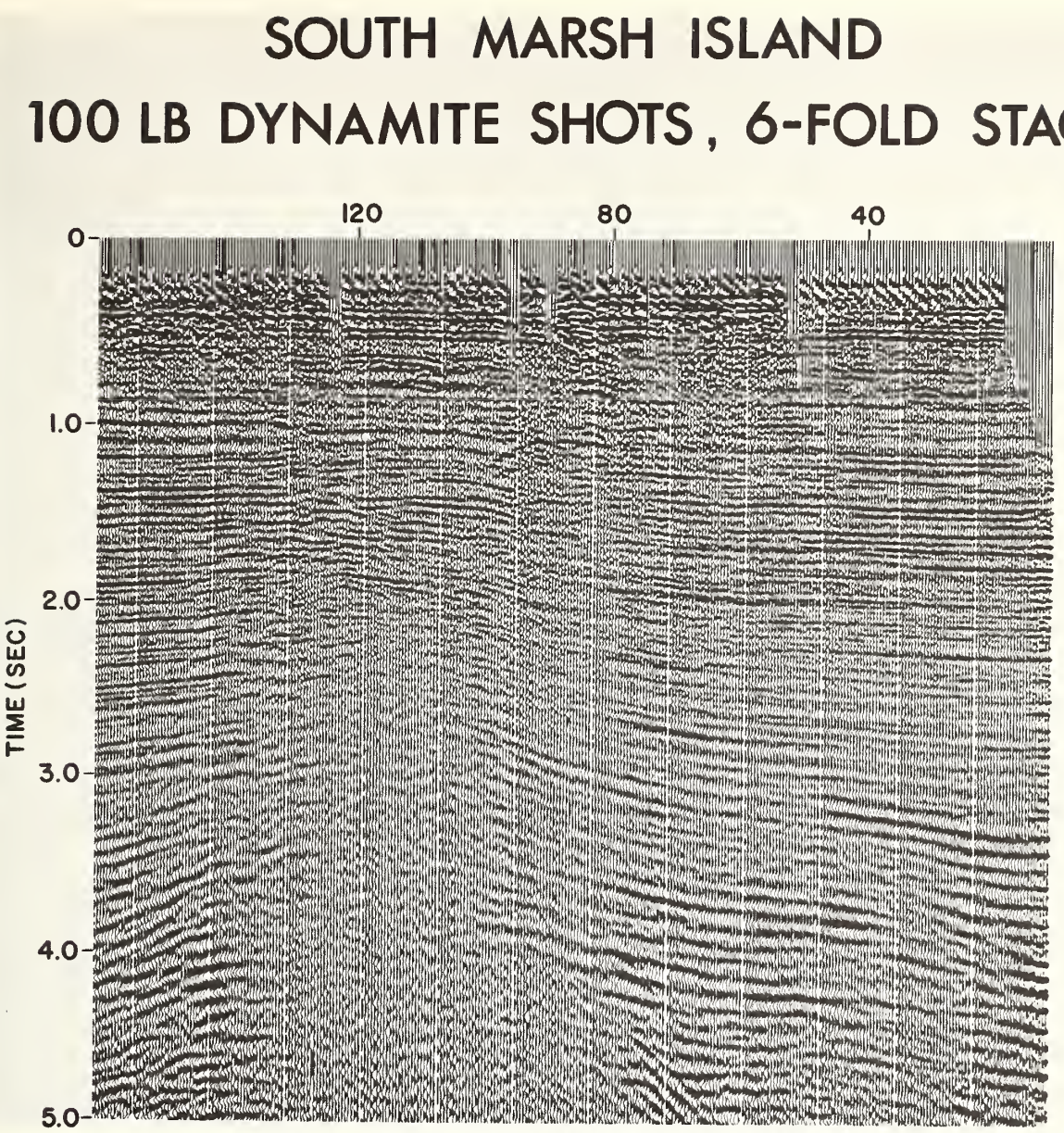

FIGURE 5.—Seismic subsurface section, nine miles in length, shows offshore Louisiana sedimentary layers to a depth greater than 20,000 feet.

existing systems a failure may result in a loss of lane count, in which case operations must be discontinued and a time-consuming transit made to a base point or the lane count must be brought out to the vessel by an aeroplane which is equipped with the identical system. Redundant systems have been used with varying degrees of success because loss of signal due to propagation effects may disable both systems (fig. 8).

As a further example of industry problems involving marine geodesy, let us examine the use of the shipborne gravity meter.

Gravity measurements at sea can be made by a remotely controlled meter lowered to the sea floor to depths as great as 600 feet. In this instance the precision is almost as high as conventional land measurements. In areas where a lower precision, of several orders of magnitude, is sufficient to achieve the exploration objective, the shipborne gravity meter is used because of its more rapid coverage and less cost per unit of traverse.

To conduct a gravity survey, the geodetic position must be known to obtain the latitude

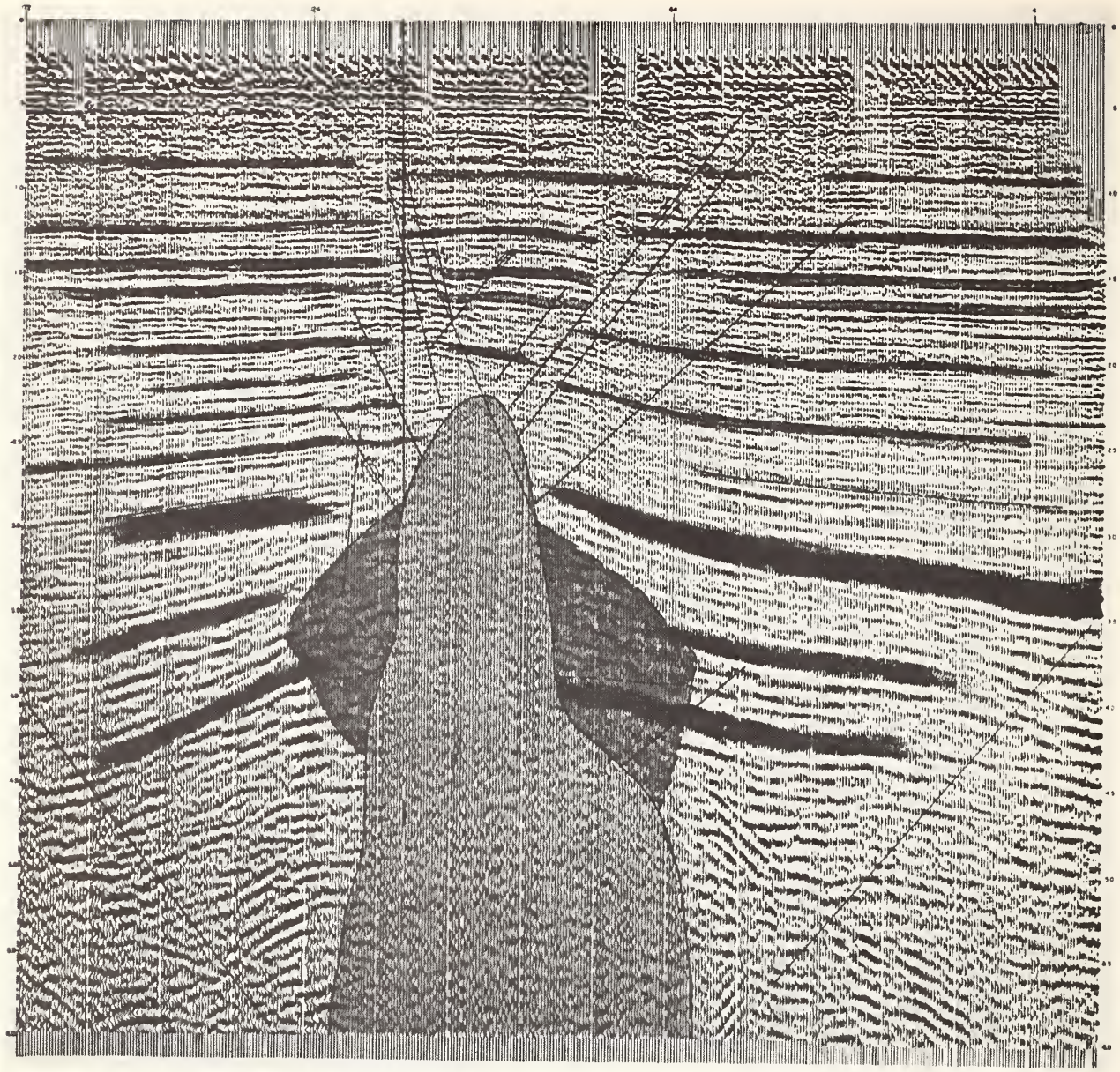

FIGURE 6.—Interpretation of data shown in figure 5 depicts a deep salt dome surrounded by a shale mass with deep sedimentary layers. A typical graben fault pattern exists above the dome.

correction, which takes into account the increase in gravity from equator to pole. At latitude 30° this correction is about 1.3 milligal per nautical mile. In gravity surveying on land the accepted accuracy for closure in feet of a horizontal transit traverse is 50 to 100 times the square root of the length of the closed loop in miles. If the closed loop is 9 miles in length, the accepted misclosure can be 150 or 300 feet. The misclosure is adjusted around the loop so the error in the geodetic location of any station will be less than the above values.

If a sea floor gravity survey with accuracy comparable to a land survey is conducted, the latitude should probably be known with a CEP (95%) of 150 feet or better (fig. 9).

A different set of problems exists when a shipborne meter is used. In this case the reading accuracy is several milligals instead of several hundredths of a milligal. Thus, the accuracy of the latitude correction no longer enters into the final survey. On the other hand, a different problem is introduced by the movement of the ship, known as the Eötvös effect. If the ship moves eastward, it increases the effective speed of rotation, thereby increasing the upward centrifugal acceleration and decreasing the apparent gravity. This effect depends upon the east or

I- SEISMIC SYSTEM PERFORMANCE REQUIREMENTS

GEODETIC LOCATION:

Repeatability Accuracy CEP 500 Feet, 95% of the Time

POSITION FIXING:

Sequential Position Fixing Accuracy - CEP 50 Feet, 95% of the Time (20 Feet Preferred)

SERVICE AREA:

200 Miles from the Coast (400 Miles Preferred)

UTILIZATION:

100% Utilization, 24 Hr/Day, All Weather

FIGURE 7.—The main geodetic requirements of the seismic system are severe and cannot be met by existing technology.

II- ADDITIONAL PERFORMANCE REQUIREMENTS

- Continuous Position Fixing With Moving Vessels
- Permanent Fix Record
- Integration With Auto-Pilot
- Simultaneous Multi-Users
- No Interference With Other Operations
- Water Depth to 1200 Feet
- High MTBF And Low MT For Repair
- Redundant Systems
- Portable Unmanned Shore Stations (prefer no shore stations)
- Worldwide Utilization

FIGURE 8.—Additional performance requirements of the seismic system can probably be achieved.

SHIPBORNE GRAVITY REQUIREMENTS

- Geodetic Location - Static

  Latitude Corrections-CEP 150 ft Mapping

- Position Fixing - Dynamic

  Eotvos Effect:
  Heading - 1°
  Speed - 1/6 knot

FIGURE 9.—The shipborne gravity method requires very accurate position-fixing.

west component of the ship's speed and the cosine of the latitude. At latitude 30°, the Eötvös effect is approximately 6 milligals for a change of 1 knot in east-west speed component. With nearly north or south courses, the effect is small but very sensitive to the ship's heading. For example, when sailing north (or south) at a speed of 10 knots, a change of 10° in heading will produce a gravity change of 10 milligals. Because of the Eötvös effect, it is necessary to determine the speed and course of the ship with high precision if the corrections are to be determined with a precision equal to that of the gravity measurement.

In recent years the performance of shipborne gravity meters has been improved to the point that the accuracy of the gravity measurement is now controlled by the errors in determination of the Eötvös effect. A minimum requirement is determinnation of ships heading to better than 1 degree and speed to better than one-sixth knot.

The development of ocean resources will result in a significant increase in seagoing activities and in the number of hazards to navigation. There will be a number of surface and submerged platforms and a very large number of service type vessels will be needed. To navigate successfully and to conduct these operations with safety and economy it will be necessary to establish permanent electronic-geodetic networks and to equip each vessel with reliable electronic position-fixing instrumentation. The system should be integrated with the ship's autopilot controls and should provide a continuous course plot. Deviations from a preplotted course would be readily discernable and corrections fed into the autopilot control.

If the trend toward increased investigation of the oceans continues, as it must, we eventually may have as much knowledge about our oceans as we have about our planets. The significance and value of this knowledge will depend upon the accuracy of the geodetic location on a worldwide basis. Investigations will be conducted far from shore. This will require systems that need no shore-based support.

The accuracy requirements of a scientific investigation are similar to those required by mineral resource development. It is necessary to know the geodetic location and to know the relative position of a series of observations, involving sequential position-fixing (fig. 10).

It is difficult to assign a CEP for the geodetic location and for sequential position-fixing because this is a function of the particular type of scientific investigation under way. There are some extensive investigations currently being conducted where the geodetic location requirement is for a CEP of 1,000 feet and the position-fixing requirement is 150 feet.

The ultimate system should cover the entire world; provide geodetic location with a CEP better than 500 feet; sequential position-fixing CEP 50 feet, with 20 feet preferred; 24-hour utilization; unmanned or no shore stations; highly

USES OF MARINE GEODESY

- Support for Scientific Investigation of Marine Phenomena
  - — Geodetic Location: CEP 1000 ft
  - — Sequential Position Fixing: CEP 150 ft

FIGURE 10.—The requirements of various scientific investigations are similar to those of exploration for resources.

SYSTEMS PRESENTLY USED-SEISMIC EXPLORATION

SYSTEM	RANGE (N mi)	FREQUENCY (KHZ)	ACCURACY (Ft)
RAYDIST DM	200	1600	25-200
LORAC	130	2000	25-200
DECCA	200	100	25-300
SHORAN	30	300,000	30-50
LORAN C	1200	100	500-2500
OMEGA-VLF	8000	10	1000-5000

FIGURE 11.—The capabilities of electronic systems presently available for seismic offshore exploration are not adequate to meet requirements.

reliable, with long MTBF and low MT; and be economically available to all users.

There are a number of different types of electronic positioning systems available with ranges from line of sight, Shoran, to Omega-VLF, with an 8,000-mile range. It is apparent that there is no single system or combination of systems that will supply the positioning requirements of range, accuracy and 24-hour utilization (fig. 11).

There are systems under development, or under partial utilization, that will provide the geodetic location requirements. For example, the Transit system, based on satellite observations, will provide a position-fix at discrete intervals during the 24-hour day with sufficient CEP. It does not satisfy the sequential position-fixing requirement. An inertial system, with drift being corrected periodically from a Transit observation, will meet some of the requirements--for example--those of navigation and safety and economy of sea support activities. However, such a system, encompassing both transit and inertial with shipborne computers, will not be economically available to many users.

In shallow water, the combination of Transit or Omega-VLF and an acoustic marine Doppler has potential but the water depth limitation of the marine Doppler must be eliminated or compensated. The Omega-VLF system accuracy and reliability is limited by propagation variables and the system is still under development. With more instrumental sophistication, and computer processing to compensate for propagation variables, and a worldwide coverage of Omega-type stations, this system will find a wide application because of its relatively low cost and simplicity.

We have had many exciting periods in industry and commerce, such as the development of the natural resources of all types on the North American continent. We are entering into another such period, involving the development of oceanic resources. It is difficult to predict just how fast or how extensive this development will be, just as we could not have predicted the magnitude and scope of land resource development.

We can be certain that the Science of Marine Geodesy will be a key contributor in this oceanic resource development. We know the geodetic requirements, the motivations are there, and we must provide the capabilities.

Apollo Ship Navigation Accuracies and Requirements for Marine Geodesy

S. S. Byrd

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With the advent of the Apollo Program in response to man's efforts to travel to the moon, a requirement was generated for greater navigational accuracies than heretofore attained from shipborne tracking stations. To grasp and understand the meaning of this requirement, one must be oriented in the role of the shipboard tracking stations in the overall worldwide Apollo tracking network.

Tracking radar systems installed onboard 5 ships along with 15 other land-based radar stations form the network. All of these stations including the ships will be utilized in varying degrees to collect and provide continuous data concerning spacecraft position and velocity relative to the earth and moon. These data, when fed into the computing facility at the Manned Spacecraft Center, Houston, Tex., will provide critical metric information to the Mission Controller for use in conducting the mission (fig. 1).

The ships will be deployed in broad ocean areas to collect vital tracking information for purposes of making GO, NO-GO, and abort decisions relative to spacecraft orbital Insertion and/or Injection. Insertion is the function relating to placing the spacecraft into earth orbit, and injection is the function relating to placing the spacecraft into lunar transfer ellipse from earth orbit. Land-based stations have been used exclusively in the past to satisfy this requirement; but due to the very long booster burn times and lunar transfer elipse geometry, the ships are now necessary.

Each ship, to satisfy Apollo mission requirements, is currently being implemented to provide a dynamic all-weather ship's attitude and geodetic position measurement capability relative to the earth's true vertical and horizontal coordinates to 3 sigma values of 20 arc-seconds (0.1 milliradian) and 1,000 feet, respectively. The measurement accuracy will be maintained for time periods approaching 2 weeks on station, in order to cover a complete Apollo lunar mission.

The ships will operate on assigned stations in broad ocean areas beyond reach of useful radio navigation aids. The geodesy of these stations must and will be known accurately enough to main-

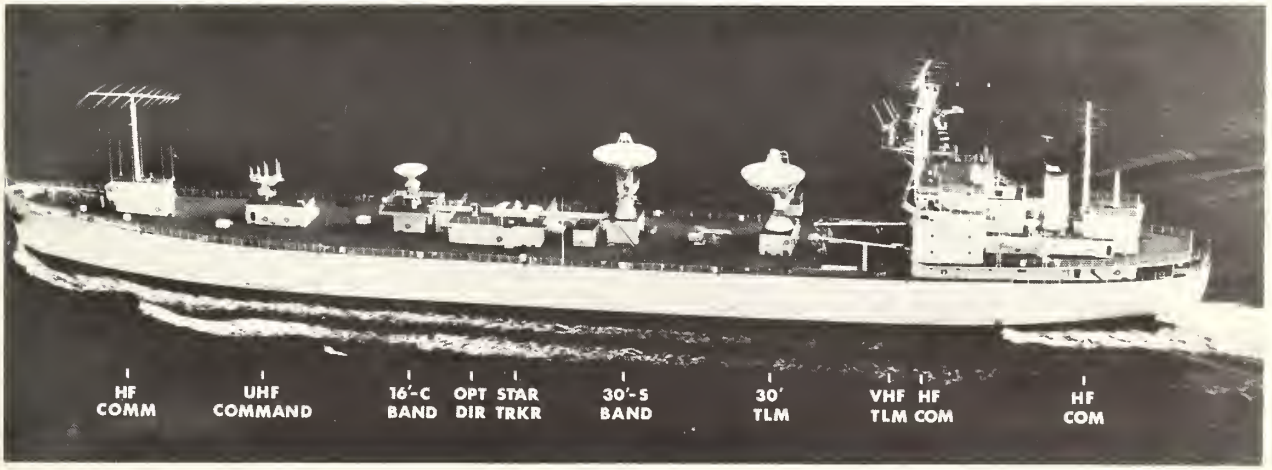

FIGURE 1.—Apollo instrument ship. Length 595 feet; speed 17 knots.

tain the desired shipboard instrumentation measurement accuracies by employment of state-of-the-art marine survey techniques, including gravity surveys which are accomplished in advance of the mission.

The a priori data obtained in this manner will be utilized to update the shipboard real-time navigation system and for data correction in the ship's Central Data Processing System. Calibration constants will thus be available for correction of systematic errors, etc.

The various techniques and equipment being employed on the Apollo ships to accomplish and maintain the required accuracies are as follows:

(1) A computer controlled Inertial Navigator with a day/night Star Tracker to provide azimuth and position updating of the navigator and for station survey operations.

(2) A satellite navigator to be used in conjunction with the Star Tracker to provide periodic ship's position information for pinpointing station locations. This navigator, operating on Doppler principles and being independent of the local gravity vertical for its output, will assist in providing knowledge of the variation between the gravity and the true vertical vectors of an operating station at sea.

(3) A Bathymetric Navigator to sound, interpolate, index, and to store on tape a digital map of specific ocean bottom areas, called bench marks, during survey operations and to recover the bench mark position in real time for navigation updating in all-weather conditions during a mission.

Of the three different sets of navigating equipment noted above, each contributing to the accuracy of the overall system, the first two sets of equipment are generally known to the scientific community and need no particular emphasis. The third set of equipment called a Bathymetric Navigator is quite new, insofar as shipboard automation is concerned and will therefore be discussed.

Under contract with the NASA/Goddard Space Flight Center, the Harris ASW Division of General Instrument Corporation is providing three prototype sets of Bathymetric Navigation Equipment for Apollo ship use. The equipment has already been delivered and installed aboard the ships. The first set will undergo at-sea evaluation testing in Sep-

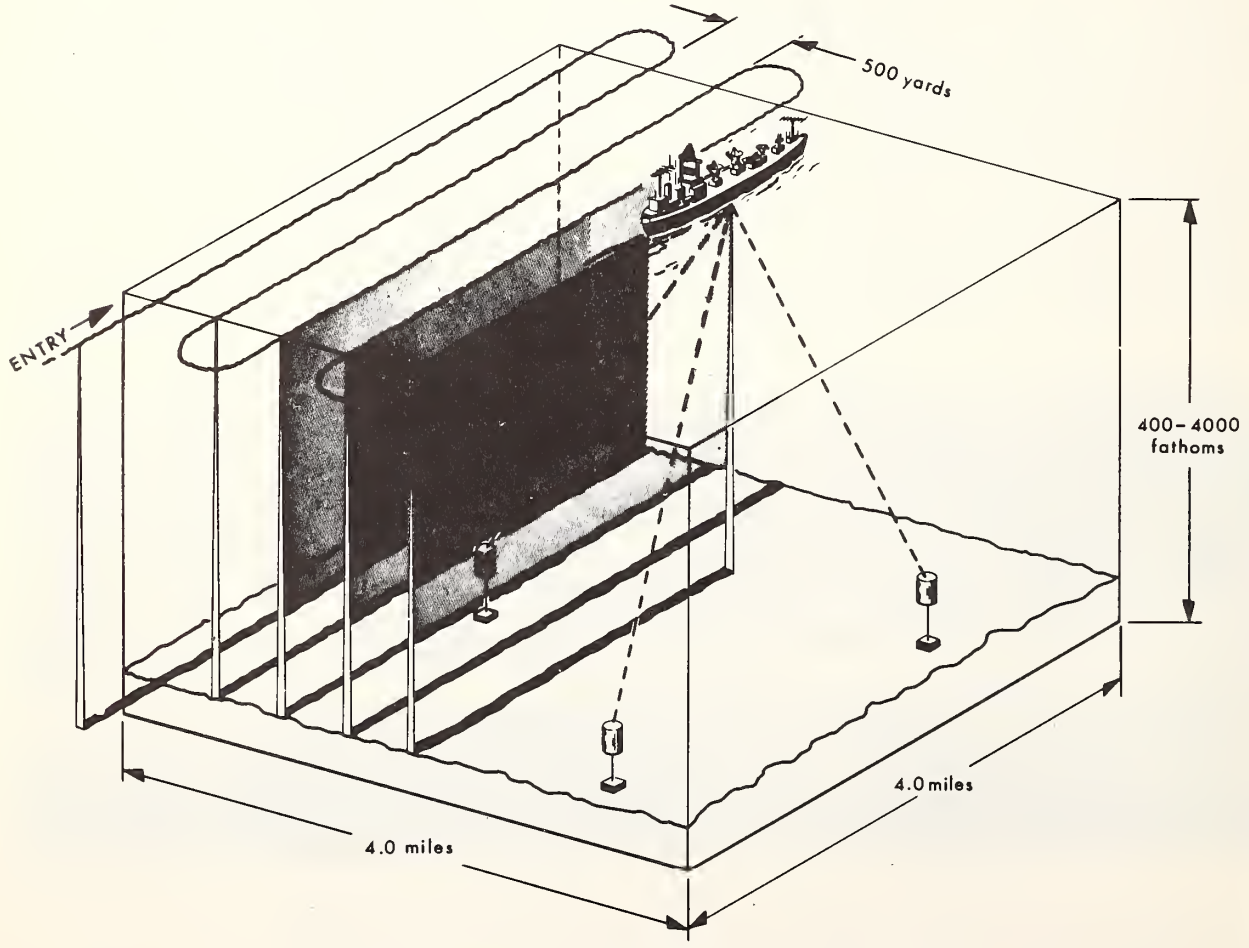

FIGURE 2.—Transponder deployment and survey sounding pattern.

tember 1966. The contract performance requirement of the system is for a CEP of 130 yards anywhere within a 4-mile-square area and 65 yards in a strip 6 miles long and 3/4 miles wide. (CEP denotes "Circle of Equal Probability" and is defined as a circle whose diameter is such that 50% of all position fixes lie within the circle and 50% outside.)

In this system the position fixing process requires two operations: Survey and Recovery. Prior to survey operations, a site is selected based on the following criteria: Area—4 x 4 miles; water depth—200 to 4,000 fathoms; topography must display r.m.s.-depth variation of at least 12 fathoms, with a normalized spectral density having an effective bandwidth of 1 cycle/mile, minimum. Depth profiles taken across the proposed area are examined for site adequacy.

After site selection, sonar transponders are planted on the ocean floor and assigned very coarse position coordinates which the ship's central computer will refine after survey operations. After the reference system has been planted, surveying is initiated (fig. 2) by steaming along one side of the square survey area. Data acquisition begins and is continued across the area by steaming over 18 alternating tracks spaced about 500 yards apart. The 180° turning maneuvers are performed outside the survey area.

During the survey run, depth data, transponder range data, Star Tracker and Inertial Navigator position data are acquired and transferred to the Central Data Process Computer where they are time-tagged and stored on magnetic tape. After sufficient data are taken, the transponder reference system is recovered for use at additional sites.

In an off-line mode, the Central Data Process Computer converts the magnetic tape raw data into a matrix which is punched on tape for use by the Bathymetric Navigator in the Recovery mode. The matrix is a table of depth values, one for each point on a rectangular grid of uniform spacing. To generate the matrix, the computer interpolates between data points on adjacent ship tracks to predict the most probable depths at locations in the matrix where depth data are lacking. The result is a grid of points evenly spaced throughout the survey area providing a continuous three-dimensional representation of the ocean floor.

Once the survey data have been reduced to matrix form and made available to the Bathymetric Navigator on punched tape, the ship's position can be recovered in two modes: Coarse Navigation and Fine Navigation. Both operations involve the comparison of new depth sounder data with the depth data in the matrix.

In a typical recovery operation (fig. 3) the system is placed in the "Coarse Navigation" mode while the ship describes a course in the direction of the matrix heading. Soundings are sampled and stored at regular intervals across the area forming a set of depth values called the coarse recovery vector. The system then determines a position fix by comparing the recovery vector with the stored matrix.

This fix can be used to re-enter the surveyed area along a diagonal using a diagonal matrix for more accurate position determination in the "Fine Navigate" mode. As long as the ship remains inside this area, accurate fixes are provided automatically every 64 yards.

The applicable ship operating stations for Apollo Insertion and Injection (fig. 4) will be located near the following coordinates:

North Atlantic Ocean	*Equatorial Atlantic Ocean*
Insertion 23°N.* 47°W.	Injection 0° 30°W.
Insertion 26°N. 53°W.	
Indian Ocean	*Caribbean Sea*
Injection 20°S. 36°E.	Insertion 12°N. 80°W.
Injection 3°N. 70°E.	
Injection 8°N. 78°E.	
Western Pacific Ocean	*Hawaii*
Injection 5°N. 177°E.	Injection 25°N. 150°W.
Injection 0° 160°E.	
Eastern Pacific Ocean	*South Pacific Ocean*
Insertion 3°S. 88°W.	Injection 25°S. 118°W.
Insertion 0° 81°W.	
Insertion 16°S. 83°W.	

*The 23°N. latitude Insertion station will vary from 21° to 25°N., depending on the lunar declination at the specific time of spacecraft launch during the month.

The requirements for marine geodesy to fulfill Apollo mission demands are as follows:

(1) The establishment of 15 to 45 bench marks at sea to within 500 feet absolute in the Atlantic, Pacific, and Indian Oceans in areas where water depths are within a 400- to 3,000-fathom range, and

(2) the establishment of error models relating the true and gravity verticals in each bench mark area to within five (5) arc-seconds.

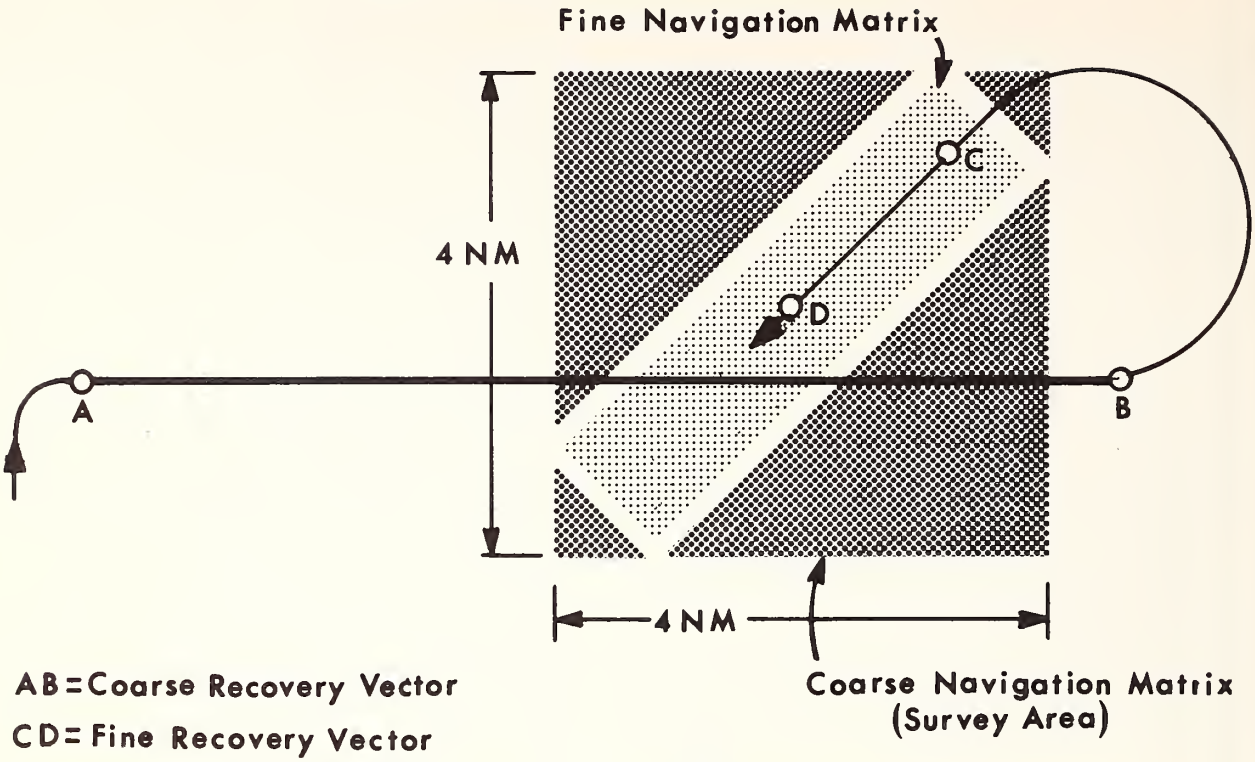

FIGURE 3.—Ship's course during recovery operation.

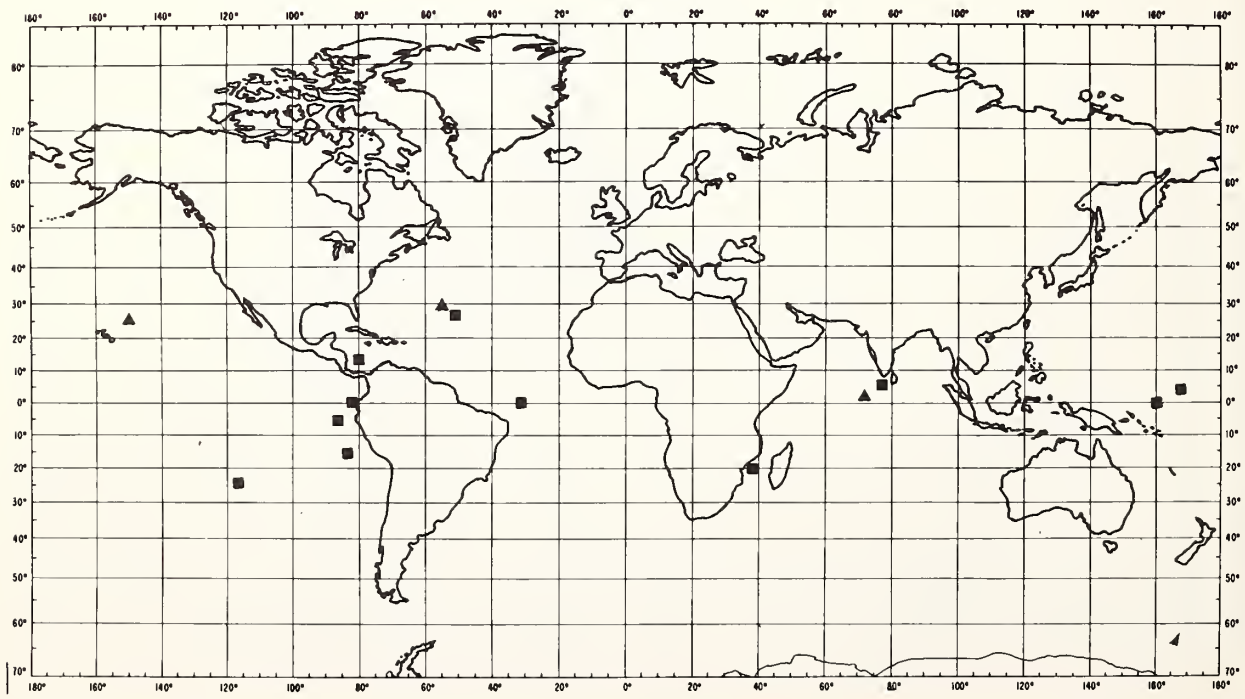

FIGURE 4.—Worldwide Apollo ship station locations. Squares indicate mandatory stations, triangles indicate highly desirable stations.

Plans and Programs of the U. S. Coast and Geodetic Survey

Capt. D. A. Jones*

U. S. Coast and Geodetic Survey
Rockville, Md.

The increasing recognition of the vast resource potential of the Continental Shelf and ocean regions has hastened the emergence of a relatively new discipline in geophysical sciences: marine geodesy. Just as classical geodesy is needed on land to increase knowledge of the size and shape of the earth, to establish precise horizontal and vertical control for mapping and cadastral surveying, and to provide essential related gravimetric and astronomic data, so marine geodesy is opportune throughout the remaining three-fourths of the earth's surface—the oceanic areas. It is apropos that the geodetic community should take the responsibility and leadership to investigate the problems, determine the requirements, and outline a program of marine geodesy.

The plans and programs of the Coast and Geodetic Survey envision the immediate requirements for marine geodesy to be horizontal control and gravity determinations; needed for exploration and development of oceanic resources of the Continental Shelf regions. Obviously, the basic geodetic networks over the entire Continental Shelf cannot be established in just a few years and with limited resources. However, activities must be initiated now to respond to the need for marine geodesy and to assure that these activities will serve the same functions that the present geodetic systems serve on the continental and island land masses. These functions include:

(1) Maintain a specified standard of accuracy over large areas and long distances,
(2) assure coordination between activities accomplished at different periods of time and at adjacent locations, and
(3) provide means to reestablish boundaries.

Geodetic surveys have been extended short distances into the marine environment to satisfy the immediate needs of the petroleum industry by using classical land techniques to locate offshore platforms and exploratory lease limits. Oceanographic activities have included gravity determinations at sea, both by surface vessels and by submersibles. Ocean-bottom gravity meters are also being employed. To date, actual marine geodetic activity has only been a "drop in the ocean."

In the immediate future, state, territorial, and international boundaries as well as exploratory property lease limits on the Continental Shelf must be located. Other oceanographic activities need geodetic positioning at great distances at sea to permit calibration of navigation systems. Structures and operations that are a hazard to navigation must be accurately located and charted. There is, therefore, an urgent need to initiate planning, research, and development for marine geodesy.

The Coast and Geodetic Survey enabling legislation authorizes the Coast and Geodetic Survey to conduct geodetic control surveys including triangulation, leveling, gravity, earth crustal measurements, and geodetic astronomy. The formation of the Environmental Science Services Administration in 1965 enhanced this authority.

The President's Science Advisory Committee's Panel on Oceanography in the report, "Effective Use of the Sea," released in July, 1966, indicates great concern within the scientific community as to the Federal Government's proper role in developing the nation's ocean program. The report states that, "The Panel believes that division of effort among government, industry, and universities appropriate to land-based activities is advisable for the oceans, and that the Federal Government should not pre-empt these activities to the extent it has, for example, in space."

Since the Coast and Geodetic Survey, by enabling legislation, is authorized to establish and maintain land-based geodetic nets for horizontal and vertical control, for gravity, and for astronomy, the Survey should, as recommended by the President's Panel, be authorized to establish basic marine geodetic nets as required to satisfy our national goals.

*On January 1, 1967, Capt. Don A. Jones assumed the position of Associate Administrator of ESSA with the rank of Rear Admiral.

The Coast and Geodetic Survey has initiated planning to undertake this basic geodetic activity on the Continental Shelf, and farther offshore as rapidly as resources become available. Fortunately, in the Coast and Geodetic Survey there is available an existing fleet of hydrographic and oceanographic vessels that is readily adaptable to marine geodetic activities. These vessels can be scheduled to support the marine geodetic program.

During the planning process, it is essential that we examine the economic factors involved. The value and the need of marine geodetic control is dependent upon concurrent technological, demographic, and economic developments. The value of a control program should be determined only after consideration of the program's interaction with other existing and potential economic activities. An investment in marine geodetic control, to establish boundary lines for petroleum leases in the Gulf of Mexico, has been made by the petroleum industry, justified on the economic aspects involved. This investment certainly would not have been made had not an analysis of the potential economic activities proven that the exact locations of the involved boundaries were of great significance.

Analysis of the economic benefits of marine geodetic control becomes much more uncertain as the time between expenditure and potential benefit increases. Until an effective model for evaluation becomes available, the Coast and Geodetic Survey must evaluate the marine geodetic program by a partial analysis on a project-by-project basis. If a fairly well-defined objective becomes apparent, an analysis of the project will develop the optimum means of achievement and the required resources. The decision to undertake the project must consider the interactions between the program and other activities, and include a cost-benefit analysis utilizing existing analytical techniques. Basic marine geodetic control and other marine geodetic programs need to be construed as supporting activities for achieving national objectives relating to the oceans.

At the present time, the Coast and Geodetic Survey maintains the horizontal and vertical networks of basic geodetic control over the land areas of the United States and possessions, and is continuing to extend and up-grade these basic networks. In addition, the Survey is assisting with the establishment of a world coverage of control by satellite methods which will provide geodetic connections between continents and island groups heretofore unattainable. A greater than average density of geodetic control points exists along the sea shores and in the near-shore environment. One horizontal control station of second-order or greater accuracy, every 4 miles along the coast line, has been the goal during recent years. This density has been exceeded along many portions of our shores. In the near-shore environment, fixed aids-to-navigation, drilling platforms, and other structures of permanent nature have been located by geodetic methods and included in the national net. Vertical control points related to the geodetic datum similarly exist, but with a less dense distribution. The vertical control points are also related with geodetic accuracy to mean sea level via continuous tidal observations. Gravity and astronomic determinations have been made at many of the existing geodetic stations. A wealth of permanently marked geodetic control points exist adjacent to the sea from which marine geodetic nets may be extended.

At the present time and for the immediate future, extension of marine geodetic control can be undertaken only as research and development programs, with specifications closely related to immediate objectives and with the results linked to subsequent research, development, and planning. The first stage of the Coast and Geodetic Survey marine geodetic program is limited in scope and in areal extent. It is anticipated that the system will, in the foreseeable future, cover very large areas and, ultimately, large portions of the oceans.

To date, the Coast and Geodetic Survey has undertaken research and development in the marine geodetic activities of sea-gravity determinations and horizontal positioning of an underwater stable platform and a passive bottom boundary marker. My colleagues from the Coast and Geodetic Survey: Captain Taylor, Dr. Orlin, and Mr. Hickley will present papers on these undertakings during this symposium.

One of the greatest problems confronting the Coast and Geodetic Survey, and the success of any program engaged in marine geodesy, is position determination at sea. The present state of the art leaves much to be desired if position accuracy at sea is to be comparable to land accuracy of location. Although the Coast and Geodetic Survey has, over a long period of time, conducted hydrographic operations for production of nautical charts, it has not been faced with the requirement of accurate geodetic position at sea. We cannot assume that the same geodetic methods can be used at sea as on land, nor can we assume that the same accuracies of positioning can be attained at sea as on land. Our methods of location will, undoubtedly, use electronic position-fixing systems and electronic line measurements, and, as we move farther offshore, satellites.

Present electronic surveying techniques provide adequate accuracy for some engineering purposes out to a distance of 100 miles, using shore points for control. In consideration of present day requirements, there does not seem to be any need for underwater control within this 100-mile limit except for the purpose of calibration of shipboard navigational systems. However, it is recognized that future requirements within this

100-mile band may be more demanding and more exacting.

During recent successful tests of a stable platform, moored to remain 100 feet below the surface while anchored 100 miles west of Los Angeles in water 4,300 feet deep, a ship which positioned itself over the platform was located by triangulation intersection from two points on San Nicolas Island. The distance involved was of the order of 30 miles. As a check in positioning, distances were measured from the two island points to the ship by the Hydrodist, and the two methods checked within the limits specified for second-order control.

As we extend beyond the Continental Shelf areas and the work progresses toward mid-ocean, the problem of horizontal positioning requires other methods of approach because of the vast distances. It seems quite likely that a system of navigational-type earth satellites in orbits of various inclinations will be required. Continuous world-wide tracking of these satellites should provide means of determining their positions in space at any given time, and observations to these satellites from ships far from land will offer a means of determining their surface positions with geodetic accuracies. Types of observations would include: Doppler, perhaps Secor, and even optical observations with cameras which could photograph the satellites against the star background. It is difficult to estimate the ultimate accuracy that these methods may provide.

We must allocate resources for research and development of position determination systems on a project-by-project basis in anticipation that these contributions will permit unforeseen breakthroughs and attainment of the accuracies required.

The Environmental Science Services Administration and the Office of Regional Economic Development recently adopted a memorandum of agreement and plan of work on cooperative projects for economic development of the Continental Shelf areas of the United States. This agreement is primarily concerned with a general study of the economic impact of the Continental Shelf areas as related to the states which are involved. The agreement includes aspects of engineering and scientific operations at sea with respect to providing geodetic control, geodetic markers on the floor of the ocean, and hydrographic, bathymetric, and geophysical surveys.

A marine geodesy pilot project scheduled for FY 1967 is planned. A geodetic marker will be located off the coast of Maine at a depth of about 200 feet. This marker will consist of a steel-clump anchor weighing about 2,000 pounds and a subsurface buoy. The buoy will be spherical, with a diameter of about 3 feet, and will be moored at a depth of 150 feet below the water's surface and attached to the clump anchor with a 1/2-inch anchor chain. It is planned to locate this marker from shipboard by echo-sounding equipment, such as the "Sea Scanner." It should be emphasized that the proposed configuration is passive. The purpose of the project is to develop and test techniques of positioning and permanency of moorings. Most of the work will be contracted to private organizations, but the project will be monitored by the Coast and Geodetic Survey.

In fiscal year 1968, a project is being considered to establish a number of horizontal control stations, spaced about 25 miles apart, in a rectangular pattern along the Maine-Massachusetts coast. These stations will be marked with metal buoys, suspended near the bottom and recoverable with sonar-type equipment. The position of the markers will be determined by one of several methods; triangulation by intersection from shore stations; distance measurement from shore stations by electronic measurement equipment such as Hydrodist; and by electronic navigational devices such as Hi-Fix. This project will assist determination of an optimum method of establishing permanent markers at sea, and will take into account the stability of the marker, the cost of installation, and an evaluation of the accuracy possible in locating these markers by various means.

The cost of establishing permanent markers at sea may prove to be high, or even prohibitive. An alternate method could be the installation of electronic positioning systems based on shore which would permit a ship to locate itself by electronic means to an accuracy of such a degree that bottom markers would not be required. We might consider upgrading three types of existing systems; namely, Raydist, Lorac B, and Loran C. As an example, these systems would provide in ascending order range control out to 75, 300, and 1,000 nautical miles, respectively. The shorter ranges would, of course, provide the higher accuracies. For the short ranges, horizontal control might be provided by a Tellurometer-type instrument, with distances measured from shore stations either to the ship or to a helicopter hovering over the ship when the range is too great for direct visibility. This alternate would give real-time geodetic positions at sea and eliminate difficult and questionable recovery of bottom-mounted or subsurface marine geodetic stations. The system could also be used for control of marine shipping with greater accuracy than is presently possible, and could conceivably result in savings to commercial shipping by increasing operating speeds and decreasing insurance rates.

Oceanographers have indicated a desire to obtain differences of elevation over great distances at sea to permit determination of sea surface slope for mass current studies. The very term "elevation at sea" connotes a paradox. Mean sea level, as defined by the geodesist, is the equipotential surface which the oceans would as-

sume if undisturbed by the tidal forces and by meteorological effects. Such a surface is the basis for vertical control and is assigned zero elevation. But, unfortunately, the surface of the sea is influenced by tidal and meteorological forces, and the so-called mean sea level is not always at zero elevation, but has a slope of its own. This has been proven by geodetic leveling between tidal stations along the coast of the United States. At any given point, to determine the difference in elevation between the sea surface and the theoretical equipotential surface it would assume without external disturbances, will require a very subtle and imaginative approach, particularly if any precision is sought. Therefore, it seems unlikely that elevations of bottom-mounted geodetic markers will be needed or can be determined with geodetic accuracy in the near future.

Simultaneously with the program for establishing geodetic control, basic gravity coverage of the Continental Shelf is to be accomplished as quickly as resources permit. Underwater gravity meters are to be used wherever possible, with approximate 10-mile spacing, to provide reconnaissance gravity mapping similar to that provided on land.

We must recognize the security aspects of the establishment of classic geodetic networks on the Continental Shelves of our coasts. Our national security could be affected by the dissemination of the data relative to these marine geodetic nets. It is, therefore, essential that, from the outset, geodesists consider this important matter and be guided accordingly.

Role of Marine Geodesy in the Scientific and Academic Community

H. Moritz

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Mr. Chairman, ladies and gentlemen, as a university professor, I feel most at home in academic matters, therefore I should like to commence with some personal views on expected academic implications of marine geodesy.

As you know, the role of the university is twofold, teaching and research. I will start with the teaching side.

We should, obviously, provide an adequate education suitable for the purpose of marine geodesy. I do not offer you any revolutionary views on this, because I think the base should be the usual geodetic education provided by American and European universities. This should be the base. Specialization should start after the master's degree. I am quite sure that marine geodesy can furnish topics for quite a few doctor's dissertations.

How the study is arranged is mainly a choice of the individual. Probably some additional courses on oceanographic subjects will be appropriate. Sooner or later, courses on marine geodesy probably will be offered by the geodesy departments of the universities concerned.

In the meantime, it will be left largely to the student, or to the individual scientist working in this field, to provide himself with the necessary background. This is not a special feature of marine geodesy. This is necessary in many other highly specialized fields of geodesy, as Captain Moitoret has said in his introduction. We are starting to know more and more about less and less. This also applies to marine geodesy, but I am opposed to specialization at too early a stage. Of course, the scope of geodesy, like that of other sciences, keeps expanding at a great rate.

I do not feel that it is the task of university education to provide all the new, sometimes controversial, developments to students in an easily digestible form, but rather to develop the student's ability to do his own thinking. Hence, a firm grasp of the principles of geodetic science combined with a good background in mathematics and physics, as I hope every geodesist has, seems to be most important.

Among the principles of geodetic science I am talking about, I mention the ability to make observations and to draw meaningful conclusions from them. This sounds simple. But, experience shows that it is not so simple to make observations and even more difficult to draw meaningful conclusions from them.

To draw meaningful conclusions requires a rather good understanding of adjustment computation, for instance of statistics--or applied statistics--because we are gathering a great amount of observations. Observations keep flowing in all the time and we must make the best use of our information. This is an elaboration on drawing meaningful conclusions.

Of course somebody may object to certain subjects of classical geodesy, if I may use the term, as opposed to marine geodesy. Triangulation does not have the same importance in marine geodesy that it has in the rest of geodesy, but the fundamentals and principles of geodesy remain the same. The requirements in mathematics and physics, however, keep increasing. I mention some mathematical techniques that have become important in modern geodesy, which includes marine geodesy to a great extent. Consider the numerical techniques as used in computers, the statistical techniques required by advances in adjustment computations, and some lesser topics, for instance the newer integral equations which are needed in actual experience with inertial systems as far as their physical side is concerned. Spectral analysis, another fashionable topic, is required for completely different problems, such as the meaningful analysis of seaborne and airborne gravimetry and for inertial navigation.

Inertial navigation requires a very good knowledge of analytical mechanics, as Commander Macomber has shown in his paper. Analytical mechanics also is indispensable to dynamic satellite geodesy in drawing conclusions about the physical gravitational field of the earth from satellite observations.

It is unnecessary to stress the all-embracing importance of electronics in all kinds of modern

systems of measurement. This aspect will be discussed by many speakers in this symposium. I am painfully aware of the need to understand electronics when I have to send an instrument back to the factory for some minor problem.

The geodesist cannot know everything, but at least he should be familiar with fundamentals. It is only when he decides to specialized – become a marine geodesist – that he should get involved in required details.

I think that the present systems of geodetic education are adequate to provide the necessary background for marine geodesy. This is my opinion; I may be wrong. I also think the American system, as practiced at Ohio State University for instance, has the advantage of being able to stress the higher geodetic aspect, if I may use this term. In Germany, to mention an example I am familiar with, the surveying aspect, as opposed to the higher aspect (this is not a qualification), is somewhat more prominent; it has to be, since we must, to a greater extent, prepare our students for cadastral service. This is our purpose. We have to do it. This difference is only natural, because many more research geodesists are needed in a large country such as the United States than in the smaller European countries. This is all I have to say about the academic implications as far as the teaching side is concerned.

The second task of a university is to do research, more specially to do basic research. In this respect, the university faculty is only a small part of a great scientific community, so I do not claim any exceptional role in research which the university is supposed to play; we are just members of a great geodetic community which does its best to promote geodesy. Cooperation within this community is promoted by scientific meetings, such as the present one, and by adequate means of communication and publication, so that important results are quickly and easily accessible to all sciences. Of particular importance are scientific organizations such as the American Geophysical Union and the various European geodetic commissions on the national level, and, on an international level, the International Association of Geodesy (IAG) of the International Union of Geodesy and Geophysics (IUGG).

In the remainder of my talk, I will propose some ideas concerning the role of marine geodesy within the IAG—within the international representation of geodesy. The IAG is divided into five sections: Section One, geometrical determinations of position; Section Two, leveling and movement of the crust; Section Three, astronomical and satellite geodesy; Section Four, measurement of gravity; and Section Five, physical geodesy. I hesitate to bring forward suggestions concerning the place of marine geodesy in the IAG, especially since Dr. Whitten, the honorary President of the IAG, would be much more competent than I am, but the topic has been assigned to me. I have no other choice than to talk about it. So I will offer a few remarks. You may accept or reject them.

What I have in mind is that the IAG may be asked to establish a permanent commission for marine geodesy which could operate within Section One. Section One is geometrical determination of position and this operation truly would fit in most closely with Section One. There already are several permanent commissions in the IAG, and I do not see any reason why marine geodesy could not be another.

How can this be done? As you all know, next year in the end of September, in Switzerland, there will be a general assembly of the International Union of Geodesy and Geophysics, including the IAG. The IAG will meet, as far as I know, in Lucerne, Switzerland, and this would be the place and the time to make suggestions. But, to have the necessary proof, to have the necessary background material, I think it is necessary that the results of this important symposium be summarized in the form of resolutions which are intended to make the geodetic community aware of the importance of marine geodesy. These resolutions might concern appropriate measures to promote the cause of marine geodesy in the next general assembly of the IUGG. Therefore, I suggest that a Resolution Committee be established in this symposium and that all participants be invited to submit proposals of resolutions. A Resolutions Committee consists naturally of members, and also a chairman. I suggest George Mourad who has devoted much of his efforts to marine geodesy.

What I have said is my personal opinion concerning the role of marine geodesy in the International Association of Geodesy. Ladies and gentlemen, I am well aware that the importance of marine geodesy extends far beyond the purely geodetic aspects. I am not a narrow-minded geodesist who thinks there is nothing else but geodesy, but I am not competent to deal with the role of marine geodesy in other scientific associations; that is why I do not say more. However, I believe that many scientists, participating in this symposium, can make important contributions to this problem of the role of promoting marine geodesy in the various scientific associations. This could be done in the panel discussion following this session. I think it is an urgent problem. It also is an opportune time, since the papers presented at the First Marine Geodesy Symposium provide an excellent opportunity for interdisciplinary cooperation. Thank you very much.

A World Mean Sea Level and Marine Geodesy

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In practice the mean sea level at a given place is chosen as the zero level for all height measurements on shore and all depth determinations at sea. Where the elevation at two different points is to be compared, however, a considerable difficulty arises: the mean sea level along the coastlines and in the open sea does not in every detail follow the shape of a geoid. The results currently at our disposal indicate that the consequent deviations in mean sea level are of the magnitude of 3 meters.

These deviations are in part attributable to the inner physical properties of the sea water, and they are thus of a hydrographic character. Meteorological factors also affect these deviations; astronomical and geological considerations are, however, of only secondary significance and may therefore be disregarded in this short survey.

Every oceanographer knows that the sea level at a given place is a function of water temperature and salinity. Since the temperature and salinity of water vary considerably between different sea regions, the mean sea level shows corresponding fluctuations.

Of the meteorological factors only the most important--wind and atmospheric pressure--need be mentioned. The effect of a wind blowing in a more or less permanent direction may be pronounced in coastal areas, especially in narrow and shallow bays. On the other hand, the sea surface reacts like an inverse barometer as far as the influence of atmospheric pressure is concerned. When air pressure increases 1 dbar. the sea level decreases 1 cm. and vice versa.

One factor to be considered in connection with studies on mean sea level is the present slight increase in air temperature in polar regions, which is followed by a weak melting of continental ice. This melting results in an increase in sea level in oceans and seas, and though the extent of the increase has been variously estimated by different scientists, it may be assumed that, on an average, it is approximately 1 mm. per year.

From the foregoing it is clear that the number of factors to be considered in the determination of mean sea level height on a world scale is considerable. In many cases the data necessary for the computation of mean sea level are still lacking, principally for the Arctic and Antarctic regions and partly for the Indian Ocean. The last mentioned area has recently been covered by extensive international research cruises, but the results have not as yet been made available on a large scale. On the other hand, for the Pacific and the Atlantic Oceans, especially for the North Atlantic, data on water temperature and salinity, and sea level records for the continental coasts and some islands, are relatively abundant. The application of the available data would, however, mean extensive and time-consuming studies on some regions, and unavoidable gaps for others. It seemed therefore more apt at this preparatory stage to aspire only to a presentation of a first approximate picture of the distribution of mean sea level on a world scale. This picture is thus to be considered only as a preliminary survey.

Any attempt to determine the mean sea level in oceans and seas has three main stages. First, the mean sea level in the deep and open areas of the oceans must be computed. This is a purely oceanographic problem, and it may suffice here to mention that the computations are based on data for the temperature and salinity of the water masses. This facilitates the determination of the corresponding water volume and its anomalies expressed in so-called dynamic heights. At this preliminary stage of study, corrections may be limited to the influence of air pressure. The second stage of research is concerned with the coastal regions, and in this connection particular attention must be paid to the piling-up effect of wind. For the determination of mean sea level along the coast both tide-gage records and geodetic measurements are of great significance, since they make possible a comparison of the results reached by different methods, and thus enable an estimate of the accuracy of the chosen

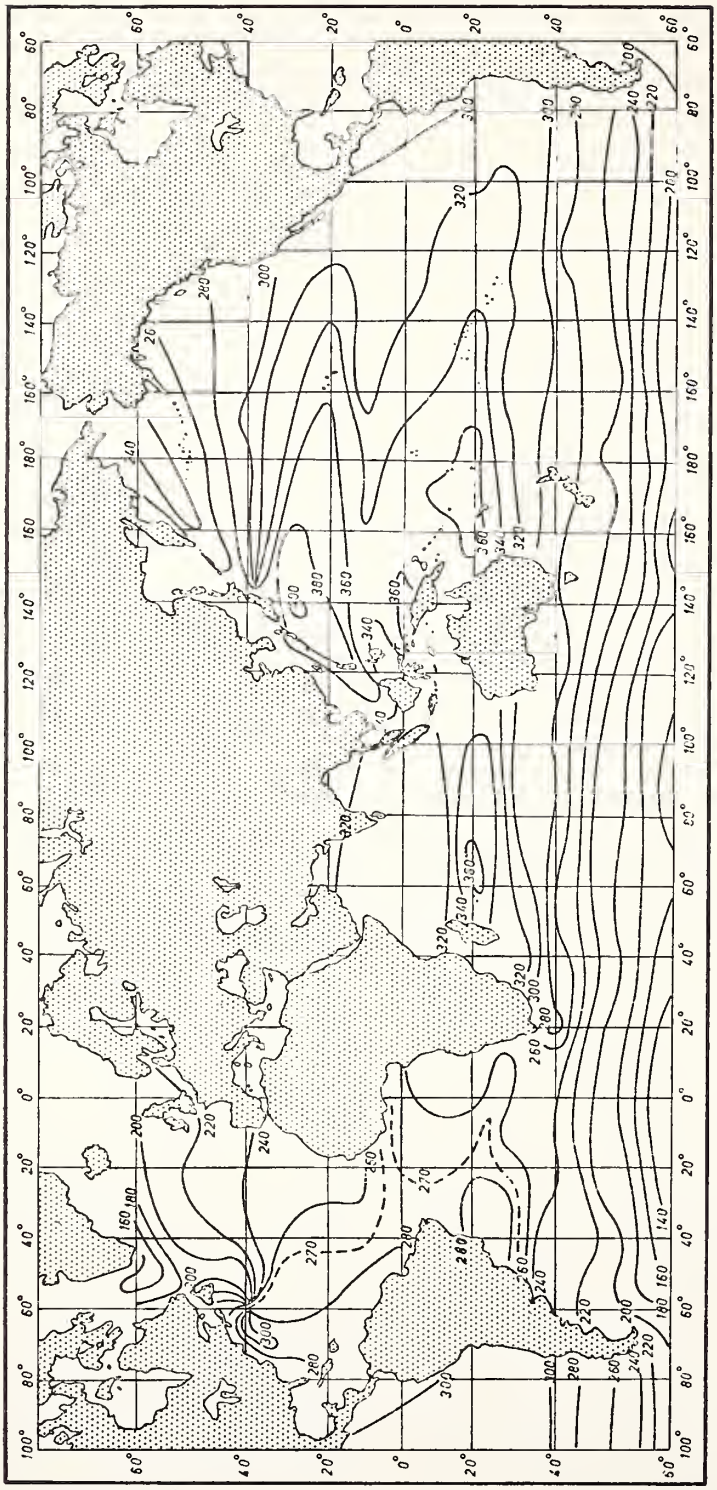

FIGURE 1.—Distribution of different heights of mean sea level (dynamic centimeters) in the world ocean.

method to be made. The third stage of the research program consists of the linking of the results for the open sea with those for the coastal areas. The comparison of conditions in particular sea basins characterized by different physical properties of the water masses and connected with each other by narrow and shallow sills also falls within this sector. Here geodetic measurements may be of considerable value.

The results for the deep sea basins of the oceans between 60°N. and 60°S. are reproduced in figure 1. For the separate oceans these results are based in part on earlier studies; for the Atlantic Ocean reference may be made to the dynamic computations of Defant, while Reid has studied the Pacific Ocean and Lacombe the Indian Ocean. The unit used in figure 1 is the dynamic centimeter, which is roughly a centimeter. From the figure the highest mean sea level in the Pacific Ocean is found off the Japanese coast, where it exceeds 400 dyn. cm. In the Indian Ocean the highest mean sea level is over 360 dyn. cm., and in the Atlantic Ocean is only 300 dyn. cm. An averaging of the mean sea level in the three oceans shows that the Pacific stands 72 dyn. cm. higher than the Atlantic, but only 36 dyn. cm. higher than the Indian Ocean. The lowest sea level in figure 1 is somewhat less than 140 dyn. cm. and occurs in the south near the Antarctic. This implies that for the oceanic regions lying between 60°N. and 60°S. the height difference in mean sea level amounts to more than 270 dyn. cm.

Although the conditions in the open parts of the oceans are, from the oceanographic point of view, more interesting than the computations of the mean sea level in adjacent and mediterranean seas, it is in connection with these basins that intensified geodetic measurements would be of the greatest importance for solving the problem as a whole. A few examples may suffice to show the significance of collaboration between geodesists and oceanographers.

An extension of the results in figure 1 to cover the Caribbean Sea allows us to estimate the mean sea level at the northern entrance to the Panama Canal at 275 cm.: on the Pacific Ocean side of the canal it is somewhat below 300 cm., let us say approximately 295 cm. The height difference of 20 cm. is close to the results of two precise levelings across the Isthmus of Panama: an old measurement gave the height difference as 18 cm., whereas according to a more recent leveling this difference amounts to 22 cm.

Another interesting case in which precise leveling has contributed to the checking of the results achieved by oceanographers is that of the linking of the Atlantic Ocean with the Indian Ocean by means of the Mediterranean Sea, the Suez Canal and the Red Sea. The mean sea level in the Mediterranean Sea at the northern entrance to the Suez Canal may be estimated as 225 cm. The results of geodetic measurements along the canal have shown that the Red Sea stands 24 cm. higher than the Mediterranean Sea. The mean sea level at the northern extremity of the Gulf of Suez should thus reach an approximate height of 250 cm. This height may also be estimated on the basis of conditions in the Indian Ocean, taking into consideration the distribution of temperature and salinity in the Red Sea. The result for the southern entrance to the Gulf of Suez is an estimated 265 cm. The discrepancy of 15 cm. may, however, be easily accounted for by possible differences in mean sea level in the Gulf of Suez as a consequence of the prevailing winds blowing over the regions from the northwest, and also by inevitable inaccuracy in the great number of approximations in the mean sea level involved in the final results.

It already has been pointed out that the present results for the mean sea level in oceans and seas are only approximate and will at many points certainly change when the relevant computations can be based on more extensive data. The ceaseless variation in the physical properties of the water masses may, however, mean that even at a later stage of research a certain amount of inaccuracy will be unavoidable. It would therefore greatly assist oceanographers if geodetic precise leveling covering the continents from coast to coast could be made. Completely different sea basins would thus be connected and such data would enable oceanographic results to be checked. Data for some selected areas of more restricted proportions such as, for instance, long peninsulas or spits of land, especially if surrounded by clusters of islands would also be of value to oceanographers, while geodetic measurements along narrow and shallow sounds and in their vicinity would certainly yield additional important information.

Significance of Open-Ocean Gravity Base Stations and Calibration Lines

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The oceans of the Earth cover seventy percent of the Earth's surface, and gravity surveys on them are far from being adequate. Recent gravity surveys have not been as productive as many investigators anticipated a few years ago. The coverage of present sea gravity surveys is spotty and often not dense enough. The situation is worst in the Southern Hemisphere. The reported accuracy of gravity anomalies at sea due to uncertainty in location and in the gravity meter reading is of the order of ± 10 mgal. Pendulums in submarines have been measuring the gravity to ± 5 mgal, or a little better. To obtain more accurate gravity anomalies, it is desirable to improve the reliability of present sea gravity measurements.

According to Woollard, the objectives of the North American gravity survey on land were to give the value of gravity at base stations within 1 mgal over a range of 5,000 mgal. Almost all land gravity base stations can be easily found. On the oceans, the finding of the exact location of a gravity base station is not so simple. To locate a station at sea, one may use known points on continents or islands, known points anchored to the ocean floor, artificial satellites, or the methods of classical astronomy. An uncertainty in latitude by one kilometer may cause an error of 0.8 mgal. Due to that error, the measurement would be taken over a different part of the ocean floor which may cause an additional error of a few milligals. Due to the many difficulties in marine gravity surveys, continental accuracy standards must be somewhat relaxed.

BASE STATION NET

A well-planned net of gravity base stations at sea must be established where the value of gravity will be obtained by gravity meters transported from land or harbor base stations. The locations of the gravity base stations at sea should have a permanent known location, they should be easily found and identified later, and the value of gravity there should be known within 1 or 2 milligals.

At some of the sea gravity base stations, gravity should be measured at various depths to get the rate of change of gravity through various water layers and also to get a check for reduction methods through sea water to the sea level. At selected base stations, continuous gravity readings should be obtained by gravimeters anchored to the ocean floor for various studies on ocean and earth tides.

Many of the gravity base stations should be multiple stations forming lanes, or better yet, dotting certain circular areas around the center station. Small gravity maps could be published for these gravity bases. The area should be large enough so that submarines, surface ships, and airplanes would be able to cross a part of the base area during a normal passage, and one would still have a check on the gravity reading. These area gravity base stations should of course be chosen at places where the ocean floor is relatively smooth and where there are no great slopes in the gravity anomaly.

From gravity base stations, gravity observations can proceed into gravimetrically unsurveyed areas. Because errors will accumulate in all series of measurements, another check at a similar or the same base station should be made as soon as the accuracy of the survey requires such a check.

The state of sea or air, and size, heading, ground speed, and navigation control of the vehicle are factors affecting gravity as measured in the vehicle. Various submarines, ships, dirigibles, and airplanes operate under their own set of circumstances. No simple and quick evaluation can be established to explain all situations in marine gravity measurements. Frequent checks at reliable gravity bases are a basic requirement for all gravity surveys. An error at the base is carried to all surveys using this base. Gravity bases form the framework for the whole net of gravity stations. The reliability of the value of gravity depends also on the calibration of the instrument, the calibration standard, the

datum control, the characteristics of the instrument which is used, the operational plans and procedures, closures, the reduction of data, and special studies dealing with the subject.

RESULTS OF OCEANIC GRAVITY SURVEYS

The normal gravity formula can be improved as the gravity anomaly coverage grows. Most of the gravity anomalies that yielded the International Gravity Formula were from land areas covering only a small portion of the Earth's surface. According to Worzel and Talwani, who based their study on 1,013 gravity stations in oceanic basins, the mean free air anomaly over the deep ocean basins is negative. From this fact it automatically follows that the mean free air anomaly is positive over the rest of the world. Worzel and Talwani found that the International Gravity Formula gives values which are 8.8 mgal too large. Possible revisions of the International Gravity Formula can be better made when the gravity anomaly coverage improves considerably in the Southern Hemisphere and also in the Northern Hemisphere.

The detailed shape of the Earth will also become better known when the oceanic gravity anomaly coverage becomes more extensive and reliable than it is now. At present, the poor gravity anomaly coverage, mainly on the oceans, causes much larger errors in the computed shape of the Earth than the defects in theoretical developments.

In addition to the usage of gravity anomalies in physical geodesy, gravity anomalies on oceans can also be used for geophysical, geological, satellite orbital, and even for some astrophysical studies.

The gravitational effects of the mantle on the oceans can be analyzed more easily than on land. This is because the gravitational effect of the sea water upon the surface gravity is rather uniform, accounting for the "first" 100 to 400 mgal. Furthermore, the solid crust is thin under the ocean floor and is generally not as complex as it is on the continents, and the upper mantle is nearer to the physical surface.

In support of gravimetric satellite geodesy, when calculating artificial satellite orbits by using gravity potential, it is of basic importance to know the gravity over the oceans. The satellites are over the oceans more than twice as long as they are over land areas.

All the fields of study that have been mentioned, and possibly some others, will benefit from the gravity surveys on oceans. The framework for a successful execution of a gravity survey is provided by a network of gravity base stations. Good gravity anomalies can only be obtained by using good gravity base stations.

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Session II Panel Discussion

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DISCUSSION

CAPT. MOITORET: I have a problem which I would like to refer to Mr. Scull. Mr. Burg stated that in addition to the geodetic problem, there is the problem of classification. He mentioned the problems of Loran C and the possible classification of Omega. I believe you, Mr. Scull, are in a better position to discuss this than anyone else, except perhaps Cdr. Macomber. Both can comment on the classification problem. Does it really exist with respect to Loran C and Omega?

MR. SCULL: I think that the problems in the classification of Loran C coordinates have been resolved. One of the problems we have had is obtaining permission from the host countries to release their coordinates on a worldwide datum. We adopted the worldwide datum, Mercury datum, for its use. At present we have received permission from, I think, all of the North Atlantic nations—Norway, Iceland, and Denmark, to release Loran C coordinates on Mercury datum. The East Coast chain and the Alaskan chain have been unclassified for quite a while. There is no problem with these. Work can be done on the other chains as soon as we can get agreement from all of the other countries. I think this will be of interest to the oil companies, mainly, in their Alaskan operations. As I said before, the Alaskan coordinates will be released on the Mercury datum. Also, I think there is work going on in the North Sea and possibly close to Newfoundland. These values will also be released. There has not been any problem with the Omega position for the Omega transmitters. They will all be on Mercury datum. This includes the Norwegian station, Trinidad station, and, of course, the stations in Hawaii and Forestport, New York. I think one of our biggest problems is now resolved.

CAPT. MOITORET: Cdr. Macomber, can you add anything to that?

CDR. MACOMBER: I believe there are two countries that have not given permission to declassification, which will keep at least something classified in the Mediterranean.

MR. SCULL: Yes, that is correct. I do not think we have determined yet from the wording of one of the countries from which we have an answer, what they actually meant. I think we are going back to try to obtain clarification. The other country in question did not answer at all. Am I correct?

CDR. MACOMBER: As I understand it, and we probably will not get an answer.

CAPT. MOITORET: Mr. Burg, does this brighten the picture any?

MR. BURG: It certainly does. This makes a lot of difference.

CAPT. MOITORET: I also have a question. Mr. Byrd, on your diagram, which shows the survey lines running about every 500 yards across the 4-mile square, there was no indication of there being any cross-check lines running in the opposite or perpendicular direction. I guess you scientists call it orthogonal, do you not? This is a normal practice in a regular hydrographic survey, and I wonder if this also is done in the NASA surveys.

MR. BYRD: We have not reached that stage. We believe that only one set of data is required on the basis that we use a wide-beam fathometer. We are not concerned about the exact detail at the bottom. The data is considered adequate if we get a relief that is repeatable. Even though the fathometer lies to us, we do not care as long as it lies the next time. Hence we get a certain amount of smoothing. Some studies, by LTD for us, show that you get a certain amount of smooth-

ing from an unstablized wide-beam fathometer, but the relief is repeatable. We have gone along with that, hoping that it will work out, but keeping the ace-in-the-hole. If it does not work out, we can always proceed orthogonally.

CAPT. MOITORET: Perhaps we can summarize the afternoon to refresh you for your questions. We have reviewed today "what are the requirements" as much as they can be stated in an unclassified meeting for marine geodesy. We have had some specific figures from certain areas from Cdr. Macomber on what are the requirements of the Department of Defense; we've mentioned requirements of industry and commerce; what are the requirements, and what has been the role of the activities of the Coast and Geodetic Survey; what are the academic and scientific communities looking at and wanting from geodesy in the ocean; what does NASA in the space program have as a requirement for tracking activities which must take place over ocean areas. This is what we have tried to present this afternoon. A lot of questions, I know, are generated, as to how do you do it, how do you get that accuracy, or how are you going to get it? That is not the question today. Please save those for tomorrow. Tomorrow's sessions, morning and afternoon, will cover technology, that is, how we do it. Those questions, we hope will be answered by some of the papers. If not, you will have some good questions for the panel, or the two panels, tomorrow. Today we are reviewing what it is we need to know and the where and why. First, do the members of the panel have any questions?

DR. HAMMER: In geophysical surveys at sea we had very serious positioning problems. An ideal solution would be a system with a passive receiver in a boat receiving signals from a satellite. My question is, what is the status of the development of such a system?

CAPT. MOITORET: The question is one that falls in the category I just mentioned. I believe we are to have a thorough exposition from people who really know. I am sure that Cdr. Macomber also knows because he was the original project officer. Tomorrow, when Dr. Newton and some of the other speakers tell us about various aspects of the satellite navigation system, and what its present and future applications are, your question will be answered. It is a "how to" question rather than a "what do we need" question.

MR. TUCKER: You mentioned politics, did you not, with regard to navigational systems? The special system you mentioned earlier when you were talking about UNESCO, I gather that it is not fully operational. Is that right?

CDR. MACOMBER: That is correct.

CAPT. MOITORET: The automated bathymetric system is not yet completely operational.

MR. TUCKER: It is not operational. I mentioned that we planned to have a full scale-test on it next month. This will mean going out and actually making the survey and processing the data after we have taken it.

CAPT. MOITORET: What accuracy requirement do you have for the tracking ship?

MR. TUCKER: A positional accuracy of 1,000 feet.

MR. WILLIAMS: I would like to make a few comments on the matter of requirements. In any new application, one finds rather unique requirements that crop up from time to time, for example, some of the problems Professor von Arx mentioned this morning. I feel that there are currently in existence techniques that can satisfy most of the specific applications. We certainly cannot say all, because we do not know what they all are. But rather than everybody starting loans for their companies, getting busy on proposals, and flooding the Naval Oceanographic Office and the Coast Survey, I think that many of you need to make a real survey in your own mind as to what your major contributions might be, keeping the problems of accuracy, economy, and frequency foremost in your mind before you come trotting around.

CAPT. MOITORET: Any question from the audience?

QUESTION FROM FLOOR: Can you tell us about the status of Omega and whether it will be classified?

MR. SCULL: As far as I know, all our efforts have been to make everything on Omega unclassified. We are very much concerned with the station coordinate problem because the people at NEL and the Omega project officer want to make this available to all the host countries that might be using the system, or have transmitters located on their continent. As far as I know, there is nothing that is classified. Every report that I have seen on Omega has been unclassified.

MR. COONS: I would like to continue in another direction. There is an effort being made to collect gravity data from all sources, including industry. However, I think I can speak for Gulf and for other oil companies when I mention that industry would not be interested in contributing gravity data to a strictly classified collection. Would anyone care to comment on the effort being made to keep the worldwide collection of gravity data unclassified?

CAPT. MOITORET: There are two possibilities, federally, for the collection of gravity data. Within the Department of Defense, a centralized DOD library for gravity data has been assigned as a responsibility and function of the Department of the Air Force which has put it in the Aeronautical Chart and Information Center in St. Louis. This is all the gravity data that they can lay their hands on, and a fair proportion is classified. Any request from anywhere in DOD, from anywhere in Government, or from anywhere in

the world, which is directed to the DOD, is referred to the Air Force to answer and supply.

MR. FREY: Although there is a lot of data that is classified there is also a lot of data that is unclassified. A viewgraph earlier showed the unclassified data. ACIC is the agency within DOD responsible for the collection of data.

CAPT MOITORET: The oil company data was formerly furnished to the Naval Oceanographic Office and some of it still is. We serve as a deputy for the Air Force, where we have the original contact to collect data that are provided to the Naval Oceanographic Office. These data are sent to St. Louis to be put into the library. Sometimes the data are not classified, but are stamped with a mark stating that it is proprietary information belonging to the particular company which furnished it to us (to the DOD) with the understanding that we would not reveal it to others; for example, competing oil companies. This procedure is still followed. The Air Force library has the same provision. That is the DOD arrangement. The national gravity data library is operated by the Coast and Geodetic Survey. They have this function, I believe, as a follow-on from the International Geophysical Year, where a data center for world gravity was established within the C&GS. I believe their data collection is unclassified. Is that correct, Dr. Orlin of C&GS?

DR. ORLIN: I would like to make a few remarks to the gentleman from the Gulf Oil Company. We at the C&GS are endeavoring to acquire all of the continental shelf gravity data so that we do not duplicate the efforts of the oil companies. I hereby offer our facilities at the C&GS to the Gulf people to pass their gravity data on to me. We will make it available to all who want it.

MR. COONS: We have been asked to supply a regional-type coverage to the government agencies and universities. We have agreed to provide regional data for the domestic United States, initially on shore, but we definitely do not want the data to become buried in files where it will not be accessible to graduate students for research study. This is our concern.

DR. ORLIN: The data will be available. You make it available on an unclassified basis and we will make it available. At present we are asking the oil companies for data at a spacing of at least 6 to 10 miles if they will not provide all of it. We will make it available, if you will make it available to us.

QUESTION FROM FLOOR: Thus far Mr. Byrd and Mr. Burg have mentioned surveys of areas with spacing of the order of several hundred feet or 50 feet, something in that order. Does anyone have a requirement for detailed surveys involving diver operations—in the sea-lab environment, for commercial programs, or perhaps the oil industries—where there is a need to locate divers and equipment within an order of feet, or several yards, rather than 50 feet? Does anyone have a requirement like that?

CAPT. MOITORET: There is a definite requirement on a case basis. The Air Force lost a bomb off Palomares, Spain, and the Navy had to find it. There was a very definite requirement for accuracies of an order of feet off Palomares, Spain. The requirement in that case was quite complicated, to know not only where one is on the surface, but also to know where the submerged working party is in a submersible, or where the equipment is at the end of a trailing cable—or as you mentioned, diving operations that require precise locations so one can go back tomorrow, pick up the task, and cover an area without leaving a gap. In that case, there is a requirement for positioning accuracies in the order of feet. To date, operations of that nature have been in water within the 100-mile limit that was mentioned to us. Captain Jones mentioned 100 miles off the coastline, where we have adequate means of fixing our position from shore stations with electronic control—well enough to meet most requirements. When you get down to the order of feet required in diving operations, I do not think anyone has defined that as a geodetic requirement. It is a relative navigational requirement, relative to somebody on the surface. Anyone can comment about it if they like.

DR. MORITZ: I think that the problem is the confusion between absolute and relative accuracy. High relative accuracies are also well-known in classical geodesy; we sometimes have to measure a distance of 100 meters with an accuracy of 1 centimeter or 1 millimeter. This is fairly common. What Cdr. Macomber meant was absolute accuracy, if I understood correctly.

MR. POWERS: I would like to ask Mr. Burg, in reference to his survey of the applications of various navigation systems, what requirement is there in geodesy for the type of navigation accuracy presented by a VLF system like Omega, which has a general positioning accuracy of around one mile, but will cover all the areas of the world?

MR. BURG: This is a good question and it raises a question I have in my own mind. When we analyze some of the results, there are indications that the system has a much better accuracy than one mile. If this is the case, it would have a geodetic application. So I am going to ask, is the potential of Omega actually better than one mile?

MR. POWERS: This is a complicated question. The simple answer is yes, under some circumstances. Generally, quoted results seem to work out to about one mile. There is a strong belief that, if you use Omega as a differential system rather than an absolute system, you can probably do better than a tenth of a mile. This has not yet been proved, but there is good circumstantial evidence that it is true.

CAPT. MOITORET: In other words, the repeatability of the system or a differential measurement from a fixed station that is receiving Omega and your position relative to it can be, I believe, given as a figure of accuracy of a tenth of a mile.

QUESTION FROM FLOOR: We heard earlier today that the meter was reevaluated by another method. Without going into the definition, we also heard that there were several differences of elevation going from water to land. My question is this, is any thought being given to actually establishing a zero point for mean sea level that can be used worldwide? We have heard that mean sea level varies slightly.

CAPT. MOITORET: Dr. Moritz, would you like to answer that one?

DR. MORITZ: No, I do not think I can answer the question.

CAPT. MOITORET: Dr. von Arx?

DR. VON ARX: I think that the definition I gave this morning, which was the standard on oceans under one atmosphere of pressure, would give a zero reference for sea level.

REPLY FROM FLOOR: That is rather hypothetical, but not practical.

QUESTION FROM FLOOR: If you start from Meades Ranch, Kansas, for the North American 1927 Datum, where would you start from for zero for mean sea level?

(Portion of discussion not transcribed.)

DR. WOOLLARD: I refer back to O. W. Williams who made a plea a few minutes ago for, if I remember correctly, economy, efficiency, and effectiveness. There have been several things brought to our attention which make me wonder whether we are really working toward this end. For example, a minute ago, Mr. Coons mentioned the problem of getting gravity data together. Mr. Frey and Dr. Orlin made comments on the same subject and Capt. Moitoret mentioned something on the subject. As I understand it, on the data obtained by the Naval Oceanographic Office from the oil companies, the stamp "for proprietary use only" is the Navy's idea and not the oil companies' idea. This has sealed off this data. I have gone around and asked many oil companies to write letters to ACIC to release this data for general scientific use. Dr. Orlin raised the point about the offshore data. The bulk of the offshore data we have was taken by a contracting group to be sold to the industry. Although Gulf may have bought the data, Gulf does not have the right to release it. We may have to wait for a period of ten to fifteen years before those that collected the data feel that offers no longer exist and that the data can be released. We have this kind of a problem. Another problem is competition among the various branches of the Department of Defense, or within a single branch for that matter. There is a duplication of effort. Also, I was impressed by the problem NASA is working on at the present moment. They are using a wide-angle fathometer and not worrying about details on the bottom. All they want to do is come back and get the same relative picture. I have a question. Are you correcting for the velocity of sound in water? Or are you hoping that when you come back later you will have the same velocity of sound in water and will get the same picture?

MR. BYRD: (First part of recorded reply not clear) Until we get more data, I really do not know how to answer your question about the velocity of sound in water.

DR. WOOLLARD. Yes, but when you start to recover the relative relief picture, you are going to have to do so on the basis of the travel time of the echo. This will change with the sound velocity structure. It may not change in 3 months, but if you come back a year later and the sound velocity conditions are different, it will make a lot of difference.

CAPT. MOITORET: I can tell you what the Oceanographic Office has done on similar types of problems. In laying out a hydrographic survey system, we must have simultaneous oceanographic observations of the speed of sound in the water at the time the depth measurements were taken.

(Portion of discussion on collection of gravity data was not clearly recorded.)

DR. HAMMER: We concur that when the Gulf Company donated data, at that time to the Coast and Geodetic Survey and also to the Navy Department, we requested that it be kept confidential until it was published. We gave complete publication rights to the agency, but we did not want this to be dribbling out to our competitors until it became available to everybody. Therefore, our request was not that it should be marked proprietary on a permanent basis, but only until it was published.

DR. WOOLLARD: I would like to say that, in general, there has been excellent cooperation between the oil companies and the scientific community and, in general, between the Coast Survey and the oil companies, and DOD and the oil companies. It is time to get these people--who are cooperating with the oil companies--to cooperate with each other. There is one other thing I want to comment on. Again this has to do with classification. I was going to save this for my talk on Friday, but I think we had better get this out in the air too. We are going to hear tomorrow a lot of technical descriptions about how well we do things and what depends on them. There are eternal questions. What is the depth of the water? What is the velocity of sound in water? Where are the shore installations connected with the navigational systems? Where are the satellite tracking stations? The people in Europe do not want us to say where these stations are. Are we going to classify the ephemeris of the satellite?

All of these things have some military value. No matter how you look at geodesy, it obviously has military value. It probably goes back to when man started throwing rocks. Now it has progressed from cannon to missiles. Gravity still is present. The thing is that for all of these systems gravitational knowledge is required. When we combine these findings with others, where are we going to draw the line and say this is the limit with which we can work? For instance, will the satellite navigator be able to work to a tenth of a mile or will he be limited to one mile? These are the things that must be resolved. The oil companies are asking for accuracies in the order of feet to drill on the ocean floor. Somewhere along the line a decision will have to be made as to where we draw the classification level. We cannot come up with the answer here, but we should all think about the problem. The success and reliability of all these systems will depend on the coordinate system and the environmental system in which you are working.

QUESTION FROM FLOOR: I wish to comment on an earlier question. If you want to know the true depth of the water, you should determine the sound velocity. However, I do not think that is what Mr. Byrd had in mind. What he has in mind is to fit a resurveyed line to a previously surveyed path, in which case velocity is not too important, it is a relative type of thing. Does that answer your question?

DR. WOOLLARD: It is good enough for me if all you want to do is recognize the same pattern.

REPLY FROM FLOOR: It is a series of such measurements correlated with a previously surveyed chart.

DR. WOOLLARD: A profile is obtained across a four-mile square. You are not depending upon absolute depth. It is the pattern that is important. The thing is, you have to have a profile you can recognize as being distinctive.

QUESTION FROM FLOOR: The International Hydrographic Bureau's original views on accuracy referred to a ratio of scale which really was related to depth of water. Is there a change in requirement for absolute accuracy of position independent of the depth of water?

CAPT. MOITORET: Just what do you mean by a change?

REPLY FROM FLOOR: At one time the accuracy of a hydrographic survey seemed to be related to the depth. Now the accuracy seems to be completely independent of depth.

CAPT. MOITORET: Yes, but the accuracy aspect is still tied to the requirements. We still have a navigational chart for normal navigational purposes. It would not change that. Now, if there is a need for a special chart for some special purpose, the surveys for that would show the change.

(At this point a large portion of the discussion could not be transcribed.)

DR. ORLIN: I would like to ask the industry representatives how far they are prepared to go for economic exploration in the ocean. We have talked about the continental shelf and possibly down to 800 or 900 feet. How far are you ready to go?

REPLY FROM FLOOR: We hear a lot of people talking about various limits, but it is very common now to talk about drilling in 1,000 feet, or going from 600 feet on out to 1,000. We hear this mentioned everywhere. It does not take long to get as deep as 1,000 feet.

DR. NETTLETON: I might comment on that. We are at the present time conducting some combined surveys in the Gulf—some 600 to 6,000 feet, that is, on the continental slope. That is the limit of two programs that I know of that are underway now. These are major oil companies and this may give some idea as to what they are thinking about for the future.

I would like to refer to the question on the possibility of obtaining an accuracy of 1,000 feet with Omega. We could make good use of it in marine gravity surveys. We are now limited as to the accuracies we can obtain with shore-based electronic systems. Since we try to drill in straight lines, we could get more or less continuous positioning good to the order of 1,000 feet; we could get an average position of a straight line that would be good enough.

DR. NEWTON: The question has come up several times about the available accuracy for the Doppler Navy navigation satellite system. The satellites in the system transmit their own ephemeris and anyone who has been lucky enough to get hold of the equipment to use the ephemeris can get equal accuracy. The ephemeris that is used is for geocentric coordinates and what we will probably have trouble with is to get people to tell you the coordinates of their position in that particular coordinate system. We have the equations and the associated constants for transforming from one system to another.

The remainder of Session II was not recorded clear enough to permit adequate transcription. The discussion centered on the various types of operations and possible duplication of effort in some localities. Capt. Moitoret clarified any misunderstanding which may have been present by defining the responsibilities and areas of interest of the different Federal agencies involved. He also emphasized the cooperation of industry in the oceanographic programs.

Underwater Acoustic Positioning: Principles and Problems

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Underwater acoustic navigation systems, consisting of a group of transponders placed on the sea floor and interrogating instrumentation on a ship deriving a position from the returns, offer capabilities which may under some circumstances compete favorably with the more conventional radio navigation methods. However, for the positioning of submerged vehicles, or for the development of fixed reference points below the ocean surface, underwater acoustics has no substantial competition. As marine geodesy is expanded toward the establishment of a control-point system throughout the oceans, it appears safe to predict that underwater acoustic positioning systems will play an important role.

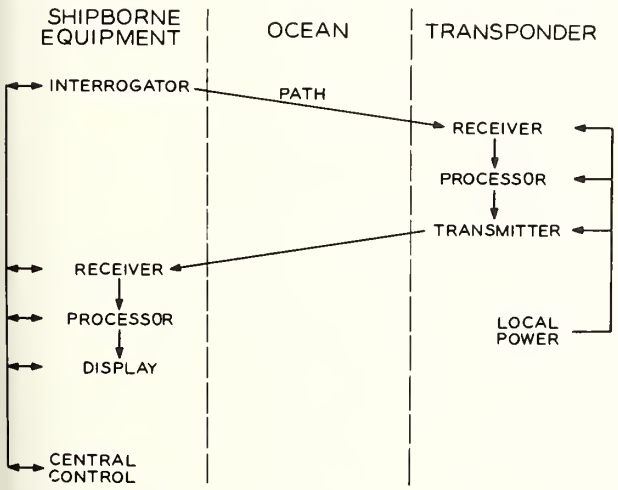

FIGURE 1.—Elements of acoustic navigational system.

Figure 1 shows the essential elements of a complete acoustic navigational system and the sequence of events involved in its operation. The first column lists the mobile elements which are loosely termed "shipborne equipment." The last column shows the essential parts of the transponder, which is placed on the ocean bottom or buoyed up from a mooring on the bottom. In between lies the ocean medium for the transmission back and forth of acoustic intelligence. The sequence of events for one complete cycle of data collection, as suggested by the arrows, is as follows. The interrogator transmits an acoustic impulse. This impulse is received by the transponder and recognized by its processor as demanding a reply, whereupon the transponder transmits another acoustic impulse back to the shipborne receiver. In a primitive system, the shipboard processing requires only the measurement of the total elapsed time between the transmitted and return impulse, that is, over the round-trip path, and the provision of computational or nomographic means to reduce this datum to a range. In a considerably more sophisticated system, the processor and display reduce and plot the data automatically. A still more elaborate step is the provision of a central control which, together with the processor and display, can be thought of as a special purpose computer for the automation of the entire operation.

This paper is concerned with acoustic paths in the ocean and the effects which water properties, underwater acoustic propagation, and noise have upon the general design of useful, workable systems. While underwater positioning systems may be useful in the shallow water over continental shelves, it is in deep water, relatively remote from land, that underwater systems really come into their own and, likewise, it is in deep water that the full complexity of underwater acoustics is encountered.[1] Therefore, attention is concentrated on the deep-water situation.

[1]Some who work with underwater acoustics may disagree with this statement, arguing that shallow-water propagation under certain conditions exhibits more complexity, for example, where semifluid or solid strata underlie the superficial bottom and affect the propagation to a substantial extent. The author cannot contest this point but feels that, within the limited sense of path geometry within the water medium, the deep-water situation can display the wider range of effects, such as shadow zones, focusing, duct transmission, and other effects.

SYSTEM CONFIGURATIONS

In order to identify the principal acoustic paths, two different kinds of systems must be distinguished. Figure 2 shows, in schematic sectional view, what may be conveniently called the surface-to-bottom system. The shipborne interrogator and receiver can be mounted directly on the hull of the ship or they can be packaged in a vehicle that is towed at a depth of a few tens or hundreds of feet by means of a relatively short cable. While the hull-mounted arrangement is obviously more convenient, it has two serious acoustic disadvantages. First, the receiver may be overwhelmed by the ship's noise. Second, the performance generally will be more reliable and predictable if both interrogator and

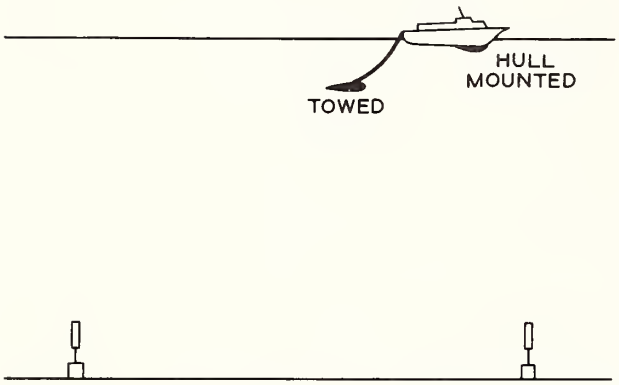

FIGURE 2.—Surface-to-bottom system showing hull-mounted and shallow-towed interrogator-receiver units.

receiver are operated at sufficient depth to avoid a variety of fluctuation effects near the surface. Hardware and techniques are now available for towing a vehicle at speeds up to 15 knots at shallow depths. Hence the need for towing does not impose a major limitation on ship mobility.

Figure 3 shows a different system, the deep-towed vehicle, which is towed at a great depth by means of a long cable. This system is radically different from the surface-based system because the acoustic paths, which will be illustrated shortly, are substantially different and also because the position of the deep-towed vehicle cannot be related directly to the towing ship—a limitation that results from the geometry of the intervening several miles of cable which cannot be readily determined. The deep-towed system is, in fact, a system for positioning of the vehicle; and the derivation of the ship's position must be accomplished by other means as a secondary objective. Deep towing is inherently a slow maneuver. Because of the weight and drag of the long cable, speeds usually must be kept below 2 knots.

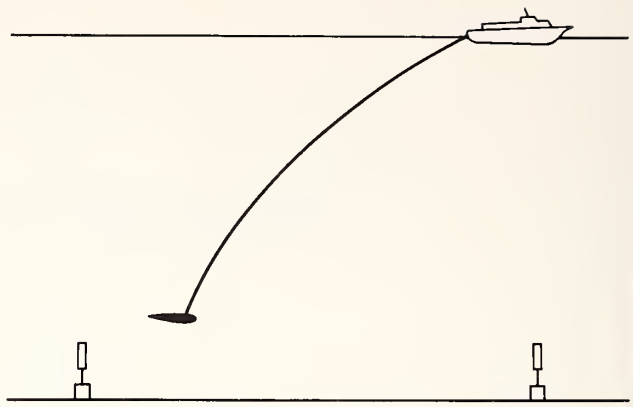

FIGURE 3.—Deep-towed system.

ACOUSTIC PATHS AND TRAVEL TIMES

The acoustic paths which are important in the shallow-towed and deep-towed configurations are determined by the variation of sound velocity with depth. Figure 4 shows sound velocity profiles for two extreme conditions in the North Atlantic Ocean.[2] During the winter season in northern latitudes, the water is cold and nearly isothermal from surface to bottom. In this case, the velocity increases monotonically with increasing depth due to the hydrostatic pressure effect. This velocity profile is labeled "northern winter" in figure 4.

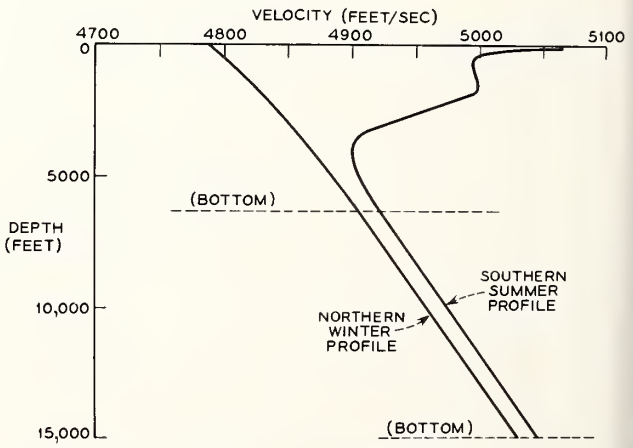

FIGURE 4.—Sound velocity profiles for two extreme conditions in the North Atlantic Ocean.

In sharp contrast, in more southern latitudes, particularly in summer, the water temperature is high at the surface and decreases slowly with increasing depth, becoming isothermal only below

[2]In the North Pacific Ocean, qualitatively similar profiles are observed, although there are detailed differences, particularly in the depth of the sound channel axis. Data from the North Atlantic Ocean are used for specific illustration, in this paper, but the general phenomena are characteristic of other comparable oceanic areas.

a few thousand feet. Sound velocity in sea water is higher at elevated temperatures, and this thermal effect is greater than the hydrostatic pressure effect in the uppermost water layers. Therefore, in the case of southern summer conditions in figure 4, the sound velocity decreases from a surface value to a pronounced minimum at about 4,000 feet, the "sound channel axis," and then increases with increasing depth similar to the northern winter profile. Local conditions of currents and stratification can introduce one or two weak subsidiary minimums near the surface.

The total variation in sound velocity from surface to bottom for a given sound velocity profile or between the northern winter and southern summer profiles is only a few percent. This might appear inconsequential, and indeed for very short paths it is, but over distances greater than a fraction of a mile the variable refractive index exerts a profound influence on path geometry. In the case of interest here, where the water depth is very great compared with the acoustic wave length, the ray paths can be calculated by differential application of Snell's law from point to point. In the usual case of velocity profiles, which cannot be closely approximated by simple mathematical relationships, the paths must be determined by numerical calculation. Computer science to perform such numerical calculations is now well developed. Therefore, if given an empirically determined profile, it is a routine computer operation to calculate, and even to plot, large numbers of ray paths for any desired purpose.

Typical ray paths for the surface-to-bottom system are shown schematically in figure 5. Sound waves transmitted from a shallow-water source at an oblique downward angle are refracted downward in the water region above the sound channel axis--where the velocity decreases with depth. Below the sound channel axis, the rays are refracted upward. Rays leaving the source at a sufficiently steep angle will strike the bottom. However, at one particular angle the rays will just graze the bottom and at lesser angles the rays will miss the bottom completely. If there is no sound channel axis, as in the northern winter profile, the ray will tend to be refracted upward from its source as suggested by the dashed line originating from the displaced sound source near the surface (fig. 5).

For any source-receiver configuration, there is usually a multiplicity of paths along which sound energy can be propagated. Except for the rather special case of sources and receivers positioned near the sound channel axis, there is only one direct path which involves no reflections at the surface and bottom boundaries. In figure 5, a bottom-reflected and surface-reflected ray is shown arriving at the point where the

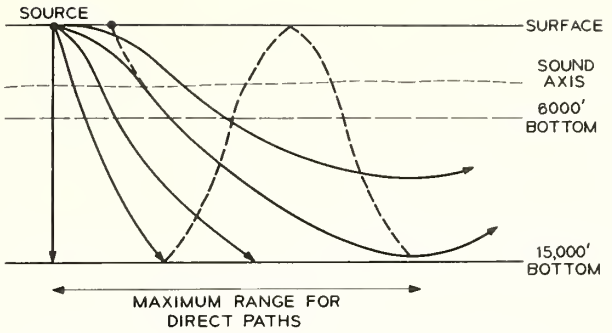

FIGURE 5.—Ray paths for surface-to-bottom system.

direct ray just misses the bottom. It also is possible for other rays, with a larger number of surface and bottom reflections, to arrive at this same point. There are at least three good reasons why these boundary-reflected rays generally are not suitable for a navigational system. (1) The reflection tends to be somewhat diffuse, that is, there is a loss of precision in timing the reflected rays. (2) The reflected rays are less reliable because the reflection coefficient from rough surfaces may be erratic. (3) It is difficult to determine the geometry of reflected rays because bottom reflections may take place from undetermined points on an irregular bottom. For these reasons, acoustic positioning systems usually employ only the direct paths.

In figures 4 and 5, flat ocean floors at depths of 6,000 feet (1,000 fathoms, approximately 1 nautical mile)[3] and 15,000 feet (2,500 fathoms, approximately 2.5 nautical miles) are indicated as typifying sensible extremes of water depth in the deep portions of the Atlantic Ocean. These two depths and the extreme velocity profiles represented in figure 4 were used for numerical calculations of ray paths. The results provide a quantitative perspective of the extremes within which the phenomena of deep water acoustic propagation will lie.[4]

For the direct surface-to-bottom paths, figure 6 shows the computed one-way travel time versus the horizontal range, that is, the projection on the surface or bottom of the curved slant ray path. One curve in figure 6 corresponds to a 6,000-foot water depth, the other to a 15,000-

[3]For the most part, English units are used in this paper, not for lack of sympathy with the metric system, but simply because water depths on most existing charts are expressed in feet or fathoms and horizontal distances are still measured in feet, yards, or nautical miles in a great proportion of marine work.

[4]It must be emphasized that the northern winter and the southern summer sound velocity profiles for the North Atlantic are extreme conditions. At any one place, the seasonal fluctuations in profile are not nearly as great as from one of these extremes to the other. In the most northern latitudes, summer insolation may create a shallow sound channel; and conversely, to the south, the near-surface velocities may be reduced perceptibly in winter. These are, nevertheless, distinctly smaller effects than those related to large changes in latitude.

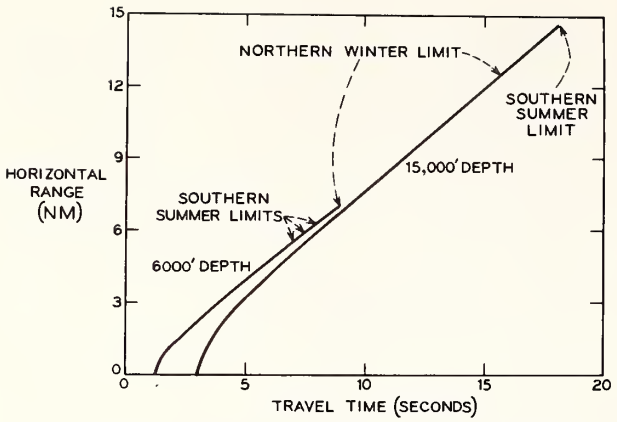

FIGURE 6.—One-way travel time and horizontal range for direct ray path of surface-to-bottom system.

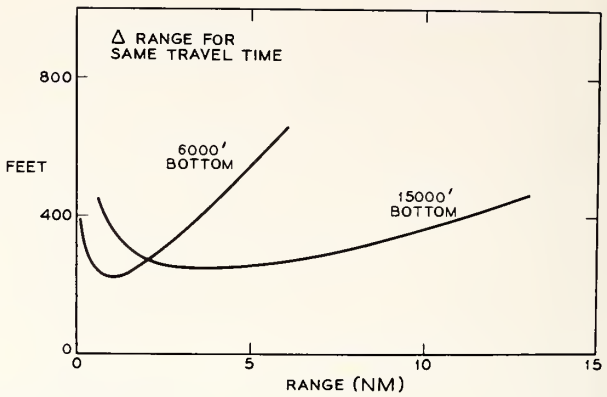

FIGURE 7.—Difference in range for given observed one-way travel time plotted as a function of range.

foot water depth. At the scale size of this graph, the curves for northern winter and southern summer conditions are so nearly coincident as to be indistinguishable from each other.[5] There are, however, differences in the maximum range of the direct paths, as noted on the figure, for the two different sound velocity profiles.[6] For short ranges, where one end point of the path is nearly overhead with respect to the other, the graphs are naturally curved, but it is interesting to note that over most of the range the relationship between horizontal range and travel time is remarkably linear.[7]

An enlarged view of the small differences between the curves for the velocity profile extremes is afforded by figure 7. Here the difference in range which would be computed, for a given observed one-way travel time, is plotted as a function of range. The differences are a few hundred feet at all ranges. If an average profile is used, disregarding all changes in velocity profile with latitude and from season to season, the derived ranges will not be in error by amounts greater than about 200 feet at almost all ranges.

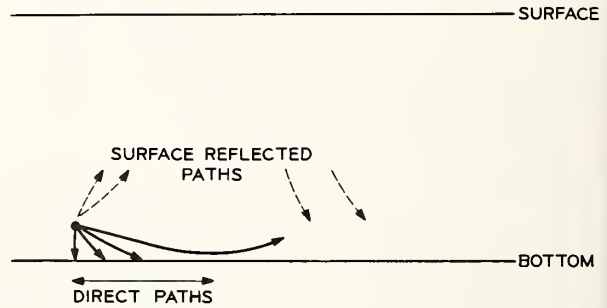

FIGURE 8.—Ray paths for deep-towed system.

Ray paths for the deep-towed system configuration are indicated schematically in figure 8. All the rays from a deep source are bent upward. Consequently, the range at which the direct rays can reach the bottom is severely dependent on the height of the source above the bottom.[8] For modest source heights, up to a few hundred feet above a 15,000-foot bottom, although the paths are perceptibly curved, the relation between range and travel time is quite closely linear,

[5]The path geometries, however, are distinctly different in the two cases. To reach a given point on the bottom and hence to attain a given horizontal range, a ray must leave the source at a steeper angle in the northern winter case than in the southern summer case. A given point on either of the curves in figure 6, therefore, corresponds to substantially different paths that reach the same point on the bottom in almost exactly the same travel time.

[6]A point of interest is the reversal of the order of the summer and winter limits for the two different water depths. In the 15,000-foot case, as implied in figure 5, the winter ranges are reduced. However, in the 6,000-foot case, the rays which approach grazing incidence on the bottom leave the source at angles approaching the horizontal in the winter case but at angles inclined slightly upwards in the summer case. Since rays refracted upward from a shallow source will suffer a reflection at the surface, they are not direct paths. Hence the maximum direct path range under southern summer conditions is determined by a ray which just grazes the surface. This leads to a lesser range than with the northern winter profile.

[7]At first glance, it seems surprising indeed that the horizontal projection of a complexly curved path is related to the travel time along the path in a nearly linear way over such a wide variation of range. This behavior can be predicted, however, from analysis of the idealized case of a linear velocity profile, which can be solved in closed form. Certain gross features of the ray path are dominated by the prolonged traverse of the deeper water within which the linear profile is a good approximation. The close linearity of range versus travel time apparently is not much perturbed by eccentricities in velocity structure nearer the surface. The implications of the near-linearity to the implementation of data reduction are obvious.

[8]The entire transponder is rarely if ever placed directly on the bottom. This would subject the acoustic paths to the effects of local topography, in the event the transponder is positioned in a depression. The usual practice, whenever feasible, is to moor the acoustic portion of the transponder a modest distance above the bottom by means of a short cable and buoyant element (liquid or solid) suitable for submersion to great depths.

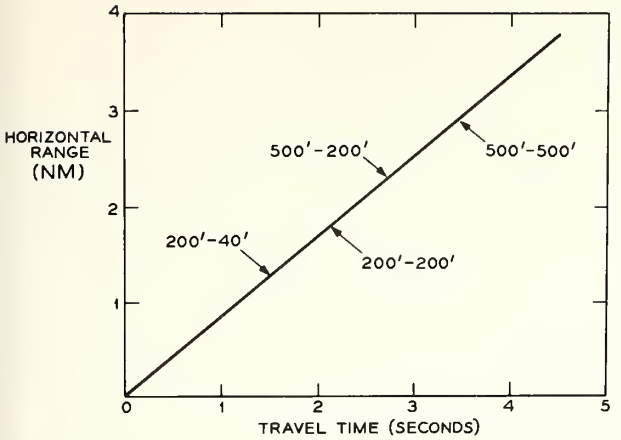

FIGURE 9.—One-way travel time and horizontal range for direct ray path of deep-towed system.

as shown by the computed results plotted in figure 9. Points are marked along the graph to indicate the maximum range corresponding to various combinations of source and receiver height above the bottom. When the sound source and receiver heights are not the same, the range-travel time curve does not remain linear near the point of origin in figure 9.

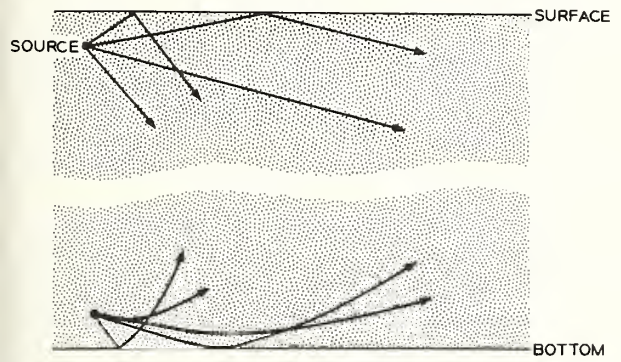

FIGURE 10.—Comparison of direct ray paths and paths reflected from surface and bottom boundaries.

When a sound source is close to the ocean surface or bottom, rays reflected from the surface or bottom, respectively, pursue paths which follow closely the direct paths. This is indicated schematically in figure 10. Because the difference in path length between direct and reflected rays is so small, the difference in their travel times also is small, as shown in figure 11—where the computed delay in milliseconds between direct and reflected paths is plotted as a function of horizontal range for sources 20 feet and 200 feet below the surface or above the bottom. As will be seen later, reflections from nearby boundaries cause effects which must be avoided or minimized by suitable selection of system parameters.

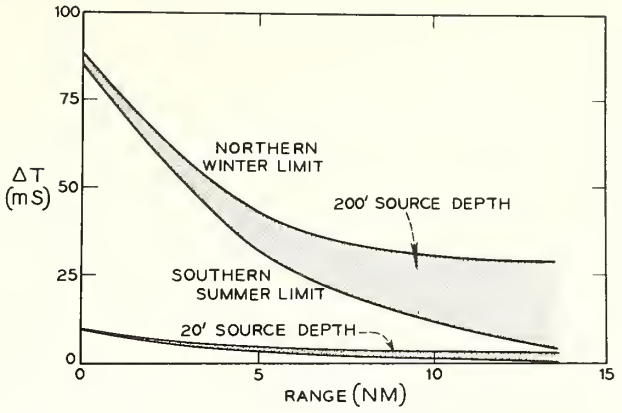

FIGURE 11.—Difference in travel time (milliseconds) between direct and reflected ray paths plotted as a function of horizontal range.

PROPAGATION LOSSES AND SEA NOISE

The question of losses along the propagation paths must next be considered. Although, as indicated in the preceding figures, the variable refractive index of the ocean introduces substantial complexity into the geometry of the propagation, spreading losses along the direct paths follow closely an inverse square law. In engineering terms, the level decreases 6 decibels (db) per distance doubled. In addition, there is an attenuation or heat loss which is exponential in character, that is, at a given frequency it will be a constant number of decibels per mile. At frequencies below one kilocycle per second,[9] attenuation is nearly negligible for ranges less than 20 miles; at frequencies somewhat above 1 kc/sec it becomes important; and at frequencies of 10 kc/sec and higher, it becomes dominant. This is shown in figure 12, a plot of loss in db (relative to an equivalent reference distance of one yard) versus range along the path in nautical miles. The uppermost curve represents spreading loss alone and is also a good approximation to the actual loss curve at very low frequencies. The remaining curves show, at successively higher frequencies, generally accepted values for observed losses in sea water.

Another vital feature of underwater acoustics is the background noise against which signals must be discerned. Like all spatial noise fields which arise from a multiplicity of small disturbances, ambient sea noise is highly statistical, showing both rapid and long-term fluctuations between wide limits. In figure 13, the spectrum level of the noise—the pressure level in decibels relative to one microbar (one dyne

[9]In this paper, frequencies are expressed in cycles per second (c.p.s.) and kilocycles per second (kc/sec) rather than in Hertz and kilohertz, partly in deference to the large established bulk of literature in the older terms, and partly by the author's preference.

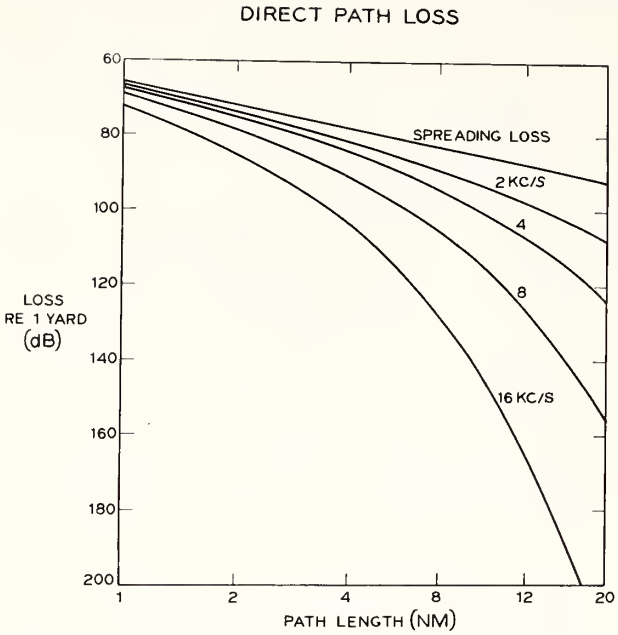

FIGURE 12.—Propagation loss along direct ray path in decibels relative to reference distance of one yard plotted as a function of path length in nautical miles.

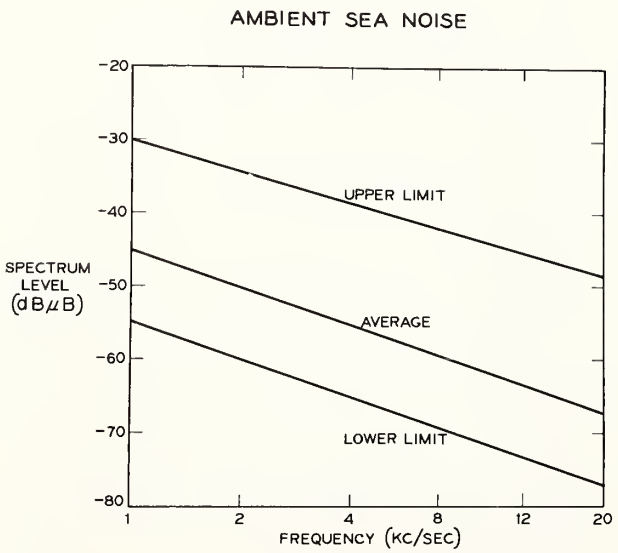

FIGURE 13.—Spectrum level of ambient noise—in decibels relative to one microbar per one-cycle bandwidth for range of frequencies of interest to acoustic navigation.

per square centimeter) for a one cycle bandwidth--is shown for the range of frequencies of interest to acoustic navigation.

Taken by themselves, the loss curves of figure 12 and the ambient noise curves of figure 13 do not convey immediate meaning for the design of underwater acoustic systems. Two specific examples will be helpful to give perspective on the power and signal-to-noise limitations encountered in the construction of practical systems. The first example, shown in figure 14,

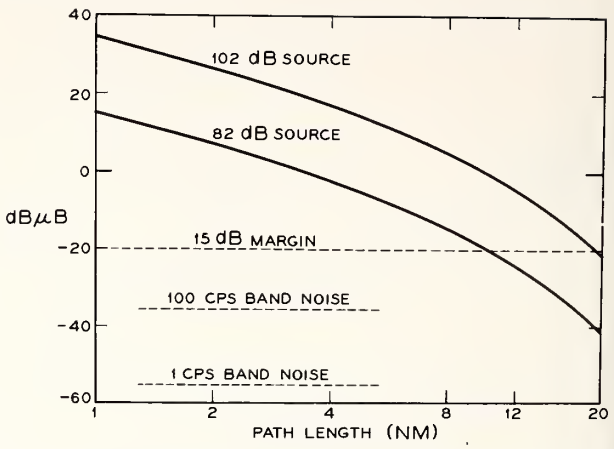

FIGURE 14.—Power and signal-to-noise limitations for a carrier frequency of 4 kilocycles per second. (Acoustic levels at receiver 4 kc/sec; no directivity.)

portrays the situation for a carrier frequency of 4 kc/sec. For two different source levels, the received level in db/μb is plotted versus path length in nautical miles. A source level of 82 db/μb at one yard corresponds to approximately 10 acoustic watts radiated omnidirectionally; the 102-db source level corresponds to approximately one kilowatt radiated omnidirectionally. The decrease of level with increasing range is in accordance with the 4 kc/sec curve of figure 12. Also on figure 14 is plotted the spectrum level or 1-cps band noise level at 4 kc/sec. For a receiving bandwidth of 100 cycles per second (a reasonable choice), the receiver noise level would be 20 db above the 1-cps level, as shown. Finally, a still higher line is drawn at which there would be a 15-db margin against the 100-cps receiving band noise.

It is apparent that even with the 102-db source, the received level at a range of about 20 miles barely provides the 15-db margin above noise, while the 82-db source falls substantially short of this figure.

The second example shown in figure 15 portrays the situation at a carrier frequency of 12 kc/sec. The noise levels are somewhat lower, but the attenuation is higher, and the net effect is that the ranges are somewhat less than at 4 kc/sec for the same margin with respect to ambient noise.

The examples are greatly oversimplified and there are a number of neglected factors that will modify the figures. No account has been taken of the directivity which could possibly be provided at the interrogator and transponder, both in transmitting and receiving. By its very nature, an acoustic positioning system must cover a very wide angle of view, and it is therefore impractical to provide more than a very modest amount of directivity. A practical limit would seem to be about 5 db corresponding to a cardioid response, with the null pointing into the bottom at the trans-

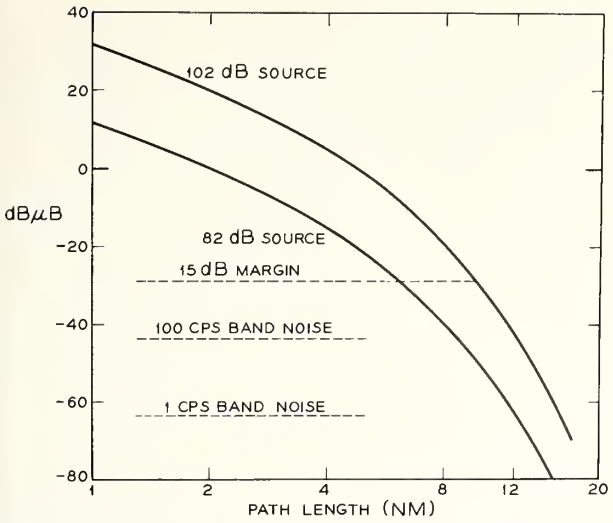

FIGURE 15.—Power and signal-to-noise limitations for a carrier frequency of 12 kilocycles per second. (Acoustic levels at receiver 12 kc/sec; no directivity.)

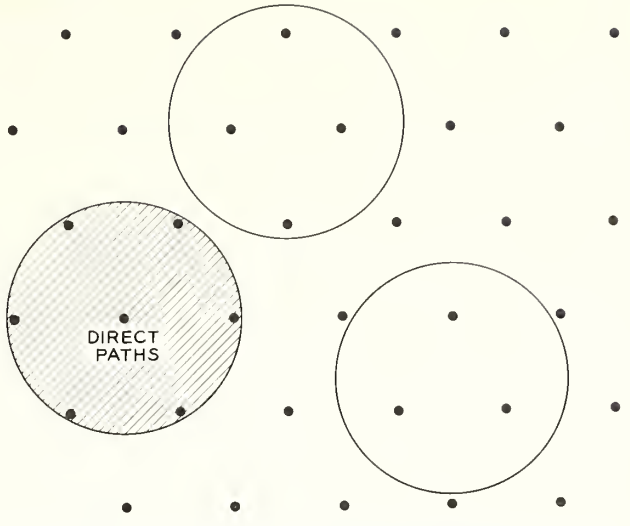

FIGURE 16.—Transponder network designed so that direct sound paths from surface can always interrogate at least three transponders—5-mile spacing for 6,000-foot water depth and 12-mile spacing for 15,000-foot water depth.

ponder and upward into the surface at the interrogator. This would provide an additional 10 db of margin against the noise. Another neglected factor is the fact that the acoustic noise field in the ocean does not correspond to smooth white noise. In addition to the relatively steady resultant of a multitude of small random noise sources, there are isolated, sporadic bursts of local noise, either manmade or biological in origin. A margin of 15 db for a system whose function is to detect pulses from an interrogator or transponder is therefore often inadequate.

Even when all of the various detailed factors are taken into careful account, the general conclusion derived from figures 14 and 15 remains valid, namely, that the underwater engineering technology must be pushed close to its limits in order to realize effective ranges in deep water out to 10-20 miles, the limit of the direct paths.

The discussion has been concerned thus far with the features of underwater propagation and noise which will influence most the selection of parameters for an operable two-way system between shipborne equipment and a single transponder. The next logical step is to consider a suitable geometry for a network of transponders, whereby an area of the ocean can be adequately marked for accurate positioning anywhere within it. While there may be no unique geometry that is optimum for all situations, figure 16 suggests a transponder network that may be appropriate for many purposes. It is an equilateral-triangular layout, with the lattice spacing so chosen that the scope of the direct paths from the surface will always include at least three transponders. This would mean a transponder spacing of about 5 miles for a 6,000-foot depth and of about 12 miles for a 15,000-foot depth. From the figure, it is clear that the number of transponders interrogated by direct paths would vary between 3 and 7 depending upon the exact position of the interrogator overhead. The significance of this observation will shortly become apparent.

SIGNAL CODING

It is appropriate to consider next the selection of suitable frequencies and the modulation scheme by which the interrogation and response are carried out. It is axiomatic that the time resolution is directly related to the reciprocal of the system bandwidth. For example, a bandwidth of 100 cps will allow a discrimination or identification of a pulse or leading edge of an impulse function to an accuracy of .01 second or 10 milliseconds, whereas a 1,000-cps system will allow resolution to one millisecond. Since the sound velocity in sea water is about 5 feet per millisecond, and since it will generally be undesirable to introduce overall system errors as great as 100 feet purely from inaccuracies of timing, an effective system bandwidth greater than 100 cps is clearly desirable. This is one major reason why acoustic navigation systems have been engineered at carrier frequencies well above 1 kc/sec. Desirable bandwidths cannot be efficiently obtained at lower frequencies. On the other hand, as the carrier frequency is increased, the losses increase rapidly, and a practical upper limit is probably reached between 15 and 20 kc/sec. Also, bandwidths should not be substantially greater than those needed for the required timing accuracy, otherwise the noise level in the receiver is unnecessarily increased.

The modulation scheme employed for the pulsed interrogation and response will depend on the number of transponders in the system. A large field of transponders presents an interesting problem

of multiplexing the operation so that individual transponders can be properly interrogated and their replies can be properly received and labeled. There are two different ways in which the multiplexing can be accomplished, frequency division

MULTIPLEX SYSTEMS

FREQUENCY DIVISION
- INDIVIDUAL FREQUENCY BANDS
- DIFFERENT SPECIES OF TRANSPONDER
- COMMON FREQUENCY ONE WAY

TIME DIVISION
- PULSE CODING
- DIFFERENT SPECIES OF TRANSPONDER
- COMMON CODING ONE WAY

FIGURE 17.—Multiplex system schemes.

and time division (fig. 17). In the frequency division scheme, a number of different frequency bands would be established, with an individual band allotted to each species of transponder. In a network such as shown in figure 16, it would clearly be necessary to have at least 7 different species of transponder. Separately interrogated, however, the transponders might reply on a common frequency band. In contrast, the time division scheme could use a common frequency band for all operations of interrogation and response. The various species of transponder differ in that they respond individually to a particular time coding of two or more pulses. If desired for the sake of simplicity, all transponders might reply with a common pulse code.

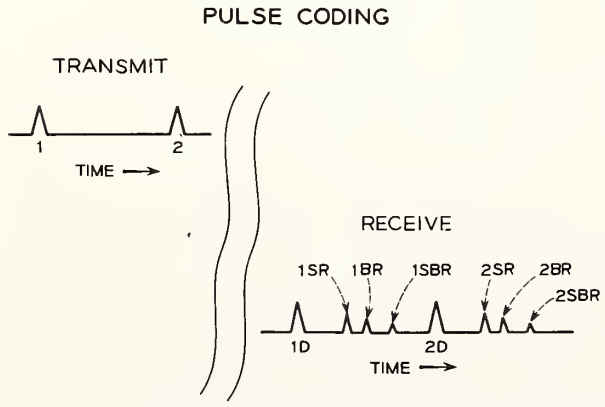

FIGURE 18.—Pulse coding in time division approach to multiplexing.

In some ways, the time division approach to multiplexing is a more elegant and more powerful approach to the problem, but there are some severe practical difficulties. Figure 18 indicates the nature of the difficulties. A case is assumed where two pulses are transmitted by an interrogator or transponder, with the coding information contained in the precise magnitude of the interval between pulses. At the other end, these two pulses are received along direct paths as pulses 1D and 2D, but also received are pulses 1SR and 2SR involving a surface reflection, pulses 1BR and 2BR from a bottom-reflected path, and pulses 1SBR and 2SBR, consisting of both surface and bottom reflections. If the interval between pulses 1 and 2 is comparable with the time delay shown in figure 11 for the reflected pulses, the ensemble of direct and reflected pulses will be most confusing and may even defy automatic recognition. This is not to say that the time division scheme is unworkable; rather, it points out the need for careful analysis of the competing paths in relation to the time-coded pulses.

Aside from this difficulty, the advantage of time division in allowing one single frequency band to be used throughout the system is more apparent than real, since the relationship of prevailing ambient noise to the signal power may be such as to require relatively narrow bands in any case. Nevertheless, in spite of the problems presented by spurious signals, problems which thus far have prevented its extensive use, time-division multiplex offers substantial advantages in coding flexibility and interrogation command of the transponder field.[10]

SYSTEM CALIBRATION

Another important question concerning the transponder field is the exact localization of each transponder. When the transponders are first planted, it is not safe to assume that their position on the bottom corresponds exactly to the dropping point on the surface. For example, if a one-knot current exists during the free fall to the bottom, the transponder may easily be laterally displaced a substantial fraction of a mile. It is virtually mandatory, therefore, to execute a series of ship runs after the field of transponders is planted, taking data from which the transponders may each be pinpointed to within the inherent accuracies of both the acoustic system and the additional system used for positioning the ship during calibration. Figure 19 suggests the way in which the ship runs should be conducted with respect to a particular transponder. A first run should be made along a line which is offset from the estimated position by an amount perhaps

[10] For example, one major advantage is that the transponder will ignore isolated noise peaks, that is, the transponder will be activated to reply only if two or more pulses properly spaced in time are received. This would prevent wasteful power drain and also would make the system less susceptible to undesired interrogation.

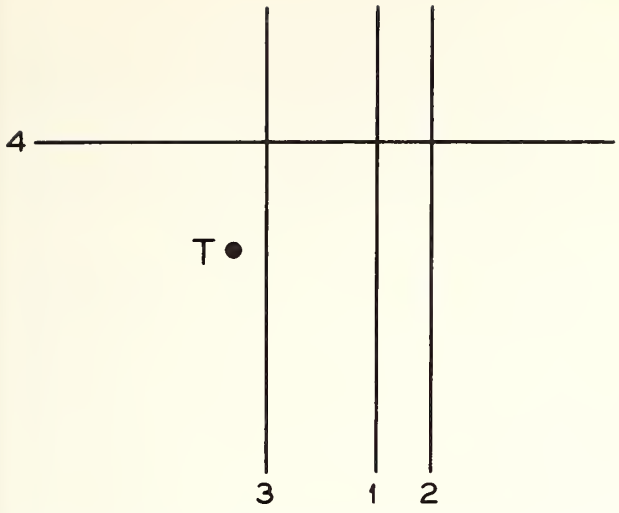

FIGURE 19.—Plan view of ship tracks during transponder localization tactics.

equal to the water depth. A second run should be made along a nearby parallel track, not only to accumulate additional data but also to make certain on which side of the previous track the transponder really lies. A third run should be made approximately over the transponder in order to determine its exact depth. Finally, a fourth run at right angles will give the position as a cross-fix relative to runs 2 and 3.

During all these runs, it is assumed that the ship maintains a steady known heading at constant speed and that electronic means are provided for accurate determination of the ship's position. Throughout a run, the transponder is interrogated at frequent intervals, and the delay time is determined for each point along the track. The data will then resemble the curves shown in figure 20, with an axis of symmetry about the point of closest approach (CPA). From the blunt shape of the curves, it is apparent that the localization will have good accuracy only when a cross fix is obtained between two runs approximately at right angles.[11]

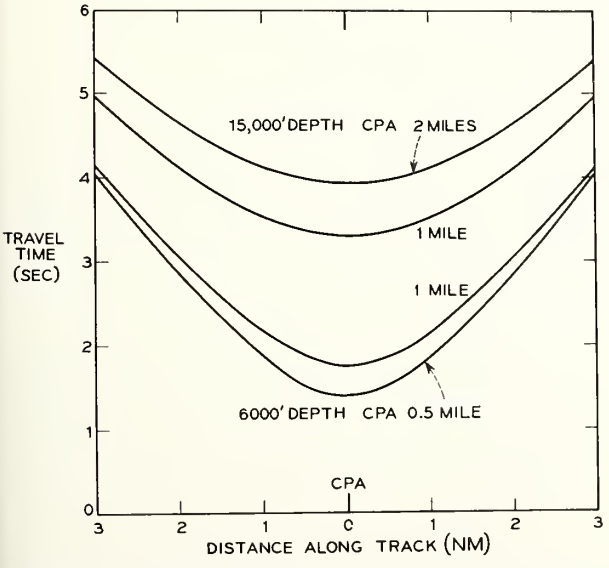

FIGURE 20.—Transponder localization data illustrating axis of symmetry for points of closest approach along each track.

SYSTEM ACCURACY

A final topic deserving brief review is the influence of the various acoustic factors and broad engineering limitations as they affect the overall accuracy of a navigation or positioning system. Figure 21 summarizes the key ideas. The term accuracy is used broadly to include all factors which will determine reliability and day-to-day repeatability of the performance.

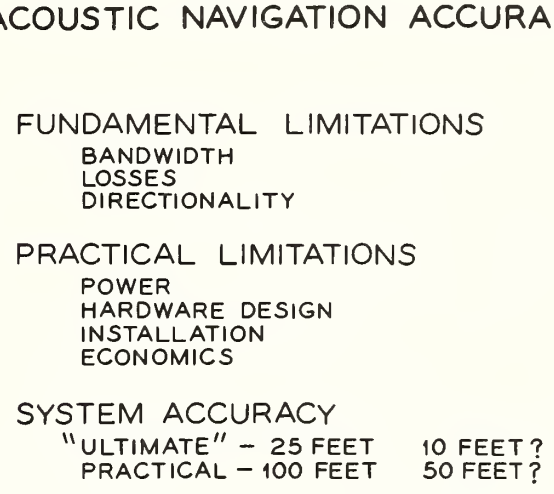

FIGURE 21.—Summary of factors affecting acoustic navigation accuracy.

Fundamental limitations are imposed by the ocean medium and by the very nature of the navigation system and its component parts. Except over very short distances, it is not possible to achieve and maintain a bandwidth greater than a few thousand cps and it is not generally practical to exceed 1,000 c.p.s. This puts definite limitations on the time resolution of received pulses and on the degree of sophistication in coding the signals. Propagation losses, out to ranges of 10 or 20 miles along direct paths, are high enough so that it is difficult to maintain a generous margin against all statistical fluctuations of ambient noise. Only a low directivity can be tolerated in the acoustic transducers, or otherwise the system would not respond suitably over a wide field of view.

There are also some general engineering limitations. The acoustic power which can be radiated

[11] The subject is covered in greater detail in the papers by H. E. Engel and others, and A. C. Campbell, session IV.

is distinctly limited, particularly in the transponder, where it is necessary to conserve battery power in order to have a long operating life. There are severe problems in designing equipment to withstand the environment of the deep ocean and to provide reliable unattended operation of the transponders. There also are limitations in the complexity of installation procedures that can be successfully carried out at sea. Finally, all phases of designing, manufacturing, installing and operating an acoustic positioning network are critically dependent upon the amount of money, available ships, trained personnel, and the needed facilities to carry out the various necessary tasks. In this respect acoustic navigation systems are similar to other kinds of marine systems now being studied and used within the broad subject area of ocean engineering.

In spite of the many uncertainties and limitations, it is worthwhile to attempt an estimate of system accuracy that can be achieved with present-day technology. Some guesses are hazarded in the lower part of figure 21. These are not meant to be accuracies which are attainable under very special conditions, but accuracies which are inherently or practically obtainable under average conditions in the deep ocean in areas remote from land.[12]

CONCLUDING REMARKS

In summary, the foregoing discussion has endeavored to bring out, or at least to imply, the following points:

(1) Ray paths must be determined and studied as an essential ingredient of system design for deep-water navigation. Ray paths can be readily determined by computerized ray tracing.

(2) Propagation losses and ambient sea noise must be known for the ocean area in question; these parameters form another important input to system design.

(3) Operating frequencies and signal coding must be selected with full regard for losses and noise, and, in the case of a large transponder field, with proper attention to the systems engineering problem of multiplexing.

(4) System calibration, the determination of the true geometry, is essential to reliable operation of an acoustic positioning network.

Several important points should be made about underwater acoustics and its future application to marine geodesy are the following. Acoustic transmission and noise are as variable as the deep oceans themselves. In almost every instance where a new ocean area is being explored, it will be necessary to measure the ambient noise and either to measure the acoustic propagation or determine those physical quantities which will allow the propagation to be calculated. Without such specific measurements, the performance of an ideally designed navigational system in a new ocean area is likely to be disappointing or even entirely unsatisfactory. However, with sufficient, preliminary, acoustic field investigations our present understanding of underwater acoustics is entirely adequate to guide the design of successful systems. Therefore it can be predicted with some confidence that acoustic positioning will be one of the building blocks in the future development of marine geodesy.

[12]No attempt has been made here to distinguish between self-consistent accuracy within a self-contained acoustic system and accuracy of relating points on the ocean bottom to well-established points on the nearest land masses. Remarks about repeatability and accuracy of acoustic positioning apply only to the self-contained case of locating a point on the bottom with respect to other nearby points on the bottom or to points on the ocean surface. Relating these points in turn to more remote points on the earth's surface must involve other approaches and other kinds of navigational systems. This aspect is discussed in the paper by Lt. Col. W. M. Robson, session III.

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Underwater Acoustic Positioning: Applications

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Scripps Institution of Oceanography
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Acoustic transponders and beacons have been used successfully in several underwater navigation situations in the ocean. The sound propagation complexity and the nature of the background noise dictate, in conjunction with the operational situation, the mechanical and electrical design of successful transponder system components. Particular elements that are treated are circuits which will recognize interrogation pulses but will not respond to other acoustic signals, acoustic transducers, and mechanical configurations for deep sea floor installations. Examples are provided of several approaches which have been used by different research and commercial organizations. The installation and use of one particular system in deep water (2,300 fathoms) in the Pacific is described and the accuracy obtained and performance of the system are discussed.

INTRODUCTION

In order to make detailed maps of the topography (or other properties) of the sea floor it is essential that one provide a reference system from which the coordinates of various charted points can be determined. If the water is shallow, adequate survey resolution can be obtained by making observations from a ship at the sea surface and under these circumstances various celestial and electromagnetic positioning techniques can be employed. When the water is deep it often is necessary to operate survey instruments (echo sounders, cameras, and magnetometers) far below the surface, either on small submarines or by towing them from larger craft at or near the surface. In deep water a tracking system must be used that can relate the survey instrument location either directly to reference points on the sea floor or to the surface ship whose position can be determined by other means. In this situation, underwater sound signals provide one of the best means for determining the location of the instrument package, primarily because acoustic energy is useful to far greater ranges in the sea than any other energy form.

Acoustic signals have been used for navigation for many years in various forms, notably the radio acoustic ranging used by the Coast and Geodetic Survey in the 1930's. However, it is only recently, with growing interest in sea floor detail and the specific problems posed by the search for the *Thresher* [Spiess and Maxwell 1964] and for the H-Bomb, that activity in this field has assumed significant proportions. This paper is concerned primarily with real systems that have been recently built and utilized in the deep ocean. Tyrrell (preceding paper) has reviewed the properties of acoustic propagation and background noise as well as some of the sources of errors which can arise to degrade acoustic systems. This paper discusses the various configurations that systems can take and gives examples, from the work of several groups, showing how these configurations have been utilized. One particular arrangement seems most useful, that consisting of fixed transponders on the sea floor which can be interrogated from an instrument-carrying vehicle to make direct determinations of range. This system is treated in more detail because it involves the work of my own research group.

GENERAL CONSIDERATIONS

As among electromagnetic systems, the most obvious distinction one notes is between systems in which one measures the travel time from source to receiver and systems which depend on measurement of difference between the time of arrival of the signal at two receivers (or between two synchronized signals at a single receiver).

In the first case the surface on which the unknown point lies is (approximately) a sphere while in the second it is an hyperbola of revolution, which, if the receivers are very close together compared with the distance to the source, can be treated as a cone. Each of these can be used as pure systems with several ranges or several "bearings" being determined, or they can be used in some mixture.

This is basically a three-dimensional problem; however, as in other surveying situations, the vertical coordinate can often be measured in a different way than the horizontal ones. The ocean provides two clear-cut, useful choices in this regard and both have been used. One is the measurement of pressure as a direct relative of the vertical coordinate and the other is the measurement of the round trip acoustic travel time to the sea surface, [Dow and Stillman, 1962] again giving the "z" coordinate in reasonably direct fashion. Although in some cases one resorts to generation of three surfaces of position to determine all three coordinates, one can alternatively measure the depth of the instrument and consider only the lines of position generated by the intersection of that horizontal plane with the spheres or hyperbolae of revolution arising from use of the acoustic paths to the reference positions.

The location of the final receiving hydrophones is a choice that can be made by the system designer. Here the choice must be among three alternatives in which the receiving elements are (1) fixed to the sea floor, although not necessarily resting on it, (2) mounted on the tending surface ship, or (3) mounted on the deep vehicle itself. The first arrangement is difficult to implement in very deep water but can be used in shallow-water situations or when many different vehicles need to be accommodated at one time in the same area, thus justifying the expense of a complex installation.

The three choices make possible thirty system combinations, which the designer has at his disposal. Perhaps the infancy of this field of endeavor is suggested by the fact that to date only seven of the thirty choices have been utilized in the open ocean. As yet, it is not possible to state with absolute assurance which combination will be most appropriate for a given set of operational and environmental circumstances.

Figure 1 lists alternatives that have not yet been utilized. A first notable point is the lack of any examples of hyperbolic systems in which the receiver is located at the instrument package or submarine being tracked. Such a configuration would be the direct analogue of many popular electromagnetic systems (Decca, Loran, Omega). This situation probably arises because of the relative difficulty of building pairs of sound sources having accurately controlled relative transmission times without actually wiring them to the shore. If use of cables is contemplated, it usually is easier to use the fixed-bottom elements as receivers as in the Sofar and MILS systems rather than to transmit from them. It may well be that such systems (with bottom-mounted transmitters) may become more essential as the num-

Basic Measurements

Loc. of Rec.	Range-Range	Range-Bearing	Hyperbolic
Instrument Package	MPL (E)	Straza (P)	
Bottom		APL (T)	MILS (P)
Surface Tender	Bendix (P)	WHOI (E), APL (T), NRL (T)	

P = pressure measurement
E = upward-looking echo sounder
T = vertical coordinate calculated from time measurements in same manner as horizontal coordinate

MPL - Marine Physical Laboratory
SIO - Scripps Institution of Oceanography
APL - Applied Physics Lab., Univ. of Washington
WHOI - Woods Hole Oceanographic Institution
NRL - Naval Research Laboratory
MILS - Missile Impact Location System

Figure 1.—Systems which have been utilized in the deep sea. Letters in parentheses indicate additional measurement used to determine depth of instrument package.

ber of users in a given area grows. It may also be, however, that such systems will never become popular since ability to make very good clocks, coupled with the low speed of sound (relative to electromagnetic radiation) makes it more appropriate to measure the one-way travel time from a sea floor transmitter keyed at predetermined intervals, and thus to use the system in a range-range rather than hyperbolic mode. Indeed some modest improvement of the nuclear powered acoustic beacon with which Underwater Sound Laboratory has experimented [Martin, Neidzwecki, and Neilsen 1966] would allow installation of appropriate sending stations without need for cabling to shore.

The widespread lack of use of pressure as a measure of the depth of the instrument arises because of lack of gages having adequate resolution at great depth. In the instances of its use indicated in the table (fig. 1), the vehicles being tracked were either close to the surface or did not have a requirement for accurate absolute knowledge of their depth. The most successful, truly deep (5 km), operating systems have utilized the upward-looking echo sounder which is capable of accuracy of a meter or so if very carefully used. An improvement of an order of magnitude in pressure-measuring technology would change this picture appreciably.

One additional point should be made relative to figure 1. There are many systems in the proposal or development stages. These are in addition to the ones listed in figure 1, which is restricted to existing systems. This indicates the rapidly growing interest in this field.

HYPERBOLIC SYSTEMS

The principal pure time-difference system in being is the Missile Impact Location System (MILS) currently in use by the missile ranges in both Atlantic and Pacific [for example see Range Manual, 1960]. These installations are the natural successors to the Sofar system developed and installed by the U.S. Navy in the late forties and early fifties based on long range sound propagation research carried out during and just after World War II by Columbia University and Woods Hole Oceanographic Institution. It has been found that a small explosive charge (a kilogram or so) detonated near the axis of the deep sound channel would be clearly audible at ranges of over a thousand kilometers at a receiver at similar depth as long as the path was not interrupted by any major topographic features.

In its present embodiment the system is used in two configurations. One relies on a pressure-triggered bomb as the energy source and utilizes single, bottom-mounted hydrophones, which are placed on continental or island slopes around the ocean basin to be monitored. The electrical signals from the hydrophones are brought ashore by wire cable and recorded along with an accurate time signal. After the acoustic signal has arrived at all receivers, time differences are determined. From the known positions of the hydrophones, the location of the instrument package is determined. The same system has been used extensively in the Pacific for location of natural acoustic sources related to earthquakes [Johnson et al., 1963]. When used thusly, the time of arrival is measured from the characteristic sharp termination of the Sofar-type signal with an uncertainty of less than a tenth of a second. For most long-path differences (100 km or more) the chief limitation is a knowledge of the mean sound velocity. However, in many areas this can be determined from existing hydrographic information to reduce uncertainties to less than 100 meters. Over-all system accuracy is variable, depending on the angle of intersection of the resulting lines of position.

In a second often-used alternative, six hydrophones are disposed over about a 10-mile region and the direct acoustic signal from the bomb or from the splash of the missile as it hits the sea surface nearby is detected. The timing accuracy is somewhat better as is the receiver geometry when the source falls within the hydrophone ring.

The applications of these systems are such that precision determination of the vertical coordinate is not essential, thus the source is assumed to be at the depth for which the pressure detonator has been set (or at the surface if the splash is used as the signal source). In principle this could be done acoustically in the short-range case although additional hydrophones would be required within the 10-mile circle to reduce any uncertainty to 10 meters or less.

RANGE-BEARING SYSTEMS

This category includes systems in which the direction of sound arrival is measured either by scanning with a directional receiver or by determining the difference in arrival time at relatively (to range) close-spaced pairs of hydrophones.

The first successful system of this type was the Three-D tracking range developed by the University of Washington Applied Physics Laboratory [U. of Wash., 1958]. The system (as with most of those discussed in this paper) provides redundant information by using four receiving hydrophones, oriented to provide pairs along each of three mutually perpendicular axes. These are mounted on a single large frame (fig. 2) that is fixed to the sea floor. A transmitting element on the frame sends out a signal to a transponder mounted on the vehicle being tracked which in turn radiates the actual tracking pulse. The tracking array is cable connected to shore, thus allowing control of the transmission instant as well as direct use of the received information at the shore establishment. From each pulse a round-trip travel time (range) is determined as

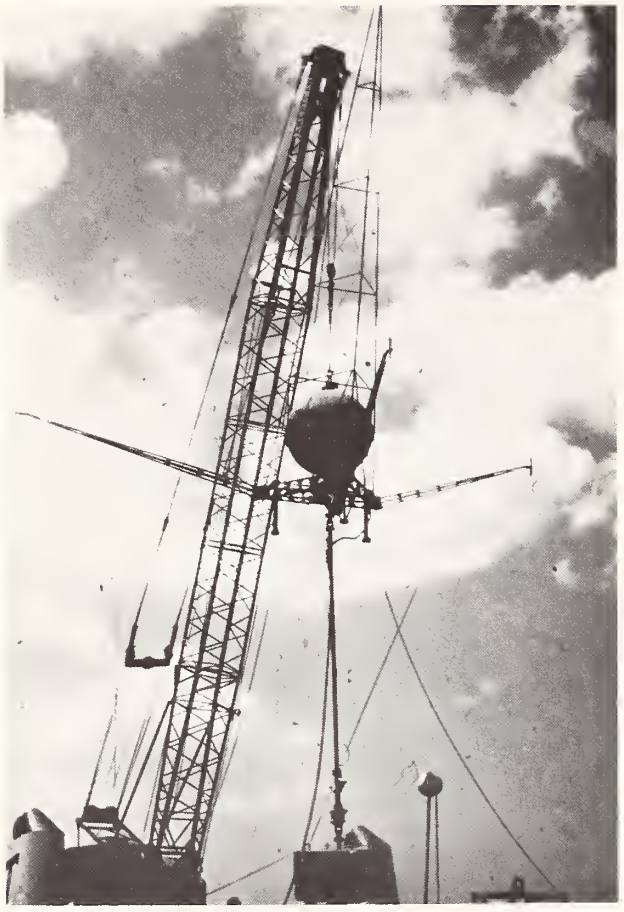

Figure 2.—Three-D array just prior to installation.

well as the time differences (direction cosines) for the three orthogonal pairs. High signal-to-noise ratio is required because the time measurements are made automatically by starting and stopping counters and are fed directly to a computer. The X, Y, and Z coordinates are determined, plotted immediately, and also are stored for future use.

Although the original system was developed and used in shallow water (about 200 meters) in an arm of Puget Sound, similar installations have now been made, at least on a temporary basis, in deep water. The Dabob Bay (Puget Sound) installation gave an accuracy of one meter or better. In other installations the accuracy was somewhat less since the dimensions were scaled up and the acoustic operating frequencies (which was about 300 kcps at Dabob Bay) were reduced proportionately. Again, knowledge of the sound velocity was to some extent the limiting factor.

Experience with this particular system led the same group to use it turned "upside down" (that is, mounted on a surface ship) to track a small unmanned submarine [Van Wagenen et al., 1963] which they developed as an instrument-carrying vehicle for studies of fine-scale temperature variations in the sea. In this case only three hydrophones (two pair) were used with the same computer techniques. Here one is faced with associating the receiving ship position with some other coordinate system if a real map is to be made. For their purposes Loran, or even dead reckoning, provide adequate accuracy.

With the loss of the submarine *Thresher* in 1963 and the subsequent trying search for her wreckage, interest in sea floor navigation grew rapidly. The Naval Research Laboratory adapted the Applied Physics Laboratory approach on other ships to provide an intermediary navigational base to establish the positions of transponders on the bottom, on towed instruments, and on small submarines (such as the bathyscaphe *Trieste*) relative to the ship, and the ship relative to a Decca or Loran C network. The NRL group's most recent installation has been on the research ship *Mizar* [Van Ness et al., 1963] for use in the successful H-Bomb recovery operations conducted last winter off the Spanish coast. While this system has been relatively successful operationally it has not been evaluated in a situation which would allow good quantitative measures of its accuracy to be determined.

During the period preceding the *Thresher* search, research groups at Woods Hole Oceanographic Institution had become interested in tracking towed instruments and had developed another similar ship-oriented system [Baxter, 1964]. Having started with longer-range propagation paths in mind than the APL group, the Woods Hole people worked at lower frequency and

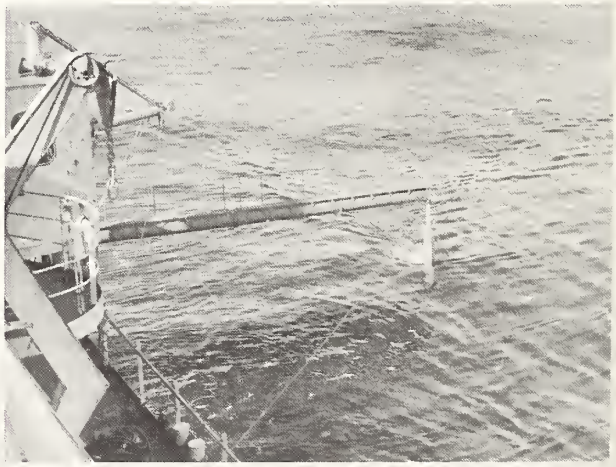

Figure 3.—Pontoon boom extended in operating position from the side of ATLANTIS II. The loose stays serve only to keep the boom extended, and to absorb towing strains when the ship is underway. The large torsional stresses of wave action on the pontoon act directly on the boom and gooseneck. Stowage is by swinging the boom alongside and lifting the pontoon from the water.

pressed for larger receiving array dimensions. Vine and Hersey developed hydrophone-carrying booms (fig. 3). These allow one element of the three to be placed 15 to 20 meters off the ship's centerline on which the other two elements are mounted. Signals in some instances were generated by a remote acoustic pinger at the instrument package and in others by a sound source controlled from the ship through an electrical connection in the instrument towing cable. Signals received at the hydrophones were displayed on a Precision Graphic Recorder (Alden Co.) and arrival times and time differences were read from the chart paper presentation. This method has only one major advantage over the direct computer input utilized by APL—it permits visual averaging with resulting improvement of accuracy under poor signal-to-noise conditions. Uncertainties in slant range were thought to be 2 or 3 meters as were errors in instrument depth, determined by an upward-looking echo sounder. Bearing errors of ±3° were expected. All the ship-mounted systems are subject to the problems introduced by the pitch and roll of the ship itself. These can severely limit the accuracy.

It appears that in comparison with other approaches different research groups have been led to use a ship-centered receiving system to determine the location of a transponder or other controlled source on the instrument package and to accept as an additional problem the navigation of the surface ship. Such an approach has the advantage of being easily carried to a new area but is strongly dependent for its usefulness on the availability of a good surface navigation system if detailed careful work is to be done. Even close to the continental United States this is difficult as was dramatized by the *Thresher* search in which no detailed work could be done at night because of lack of reliable electromagnetic propagation. It appears that for good, consistent surveying the use of bench marks on the sea floor is essential and could even make use of ship-mounted systems of this type more effective.

One other type of range-bearing system has been used. This was developed from the fact that originally the bathyscaphe *Trieste,* and more recently the small submarine *Alvin,* utilized an FM search sonar manufactured by Straza. Some transponders also have been fabricated for use by these craft. The sonar and transponder thus constitute a system which provides a measure of range (within the maximum limitation of the sonar display) to be measured on a cathode ray tube presentation and direction determined by sweeping the transmit-receive beam azimuthally across the bearing of the transponder. The resulting system is good for guiding the submarine to the transponder but lacks ability to display either variable in such a way as to allow satisfactory determination of successive positions at ranges of even a mile for survey purposes. The basic acoustic information is available in the vicinity of the receivers on the submarine. Hence, with a little more sophistication in reception and display, an accurate system of this type could be devised.

RANGE-RANGE SYSTEMS

Measurement of acoustic travel times using either transponders or precision oscillators to give a common time base is a straightforward problem. With good signal-to-noise ratios the arrival times of pulses in the frequency range useful for navigation can be determined to a millisecond or better, corresponding to an uncertainty of a meter or so. Under such circumstances it is useful to exploit this capability by assembling systems utilizing several acoustic bench marks, and then navigating solely by determining the range of the instrument package from each of them. The key element in such a system is the marker itself, for which there are two basic choices—a transponder which will return a signal when it hears one, or a programmed pinger which will transmit at accurately predetermined times. Since the user's control of the transmitting program contributes strongly to his ability to work with several beacons at once, there is a strong tendency toward preference for transponders.

Figure 4.—Bendix recoverable transponder.

While several groups seem to have built transponders, only two (Bendix and the group at the Marine Physical Laboratory) have conducted significant sea operations using them in range-range type complete systems. The transponders of the two groups, while basically similar, are quite different in design philosophy. The Bendix organization [Cline, 1966] had acoustic telemetering requirements which dictated rather heavy power drain. For this reason, they have built large units (fig. 4) which are recovered at the

conclusion of the operation. The MPL group decided [Spiess et al., 1966] to push for low cost, low power requirements, and small size to facilitate launching from small research ships. We elected to make the units have relatively long life (about a year) and not to attempt to recover them.

Because of my own close knowledge of the situation and because I feel that a detailed examination of the approach used and results obtained with a particular system will be of interest I will discuss the design and utilization of our system in somewhat more detail than the others.

Our goal was to track the motion of a deeply towed instrument—on the end of 5 to 8 km of wire—as it recorded echo soundings, magnetometer readings and other information near the sea floor. We felt that we should strive for accuracy of a meter or so in position, although we would be satisfied with 10 meters. An area of coverage of a few miles was desirable, although we were well aware that the major limitation in range for any single transponder would be the acoustic shadow produced by combination of upward refraction of the sound energy and the presence of the sea floor. Since we were to be connected by an electrical conducting cable between the ship and the towed instrument, we could have the advantage of transmitting and receiving signals from the body being navigated, and also the advantage of laboratory space on board ship for data recording, display, and analysis.

A transponder, typical of those we have built, is shown in figure 5. Each one will answer a call made at some one of three frequencies (10.0, 10.5 or 11.0 kcps) and will reply at 12.0 kcps. The individual units are capable of listening for over a year and of making at least a million replies using a modest package (48" long, 6" diameter) of Eveready Alkaline cells (No. E 97S). The key element in the transponder is the recognition circuit which essentially compares the signal level in a narrow band with that in a somewhat wider band and activates the transmitter if the ratio of the signals exceeds a particular threshold. A more detailed decription of these units is given by McGehee and Boegeman, [1966].

The shipboard equipment includes a programmer which selects the frequency for the transmitted interrogation pulse according to the operator's preset choice of sequence based on a standard 1 second repetition rate to match the 0.6 second disabled time of any transponder following a transmitted pulse. The received signals are displayed on a Gifft Graphic Depth Recorder from which the travel times for individual signals are read. Once each signal has been identified, continuity of contact allows one to work with several traces on a single display, although if the ship is in more or less steady motion, contact with a

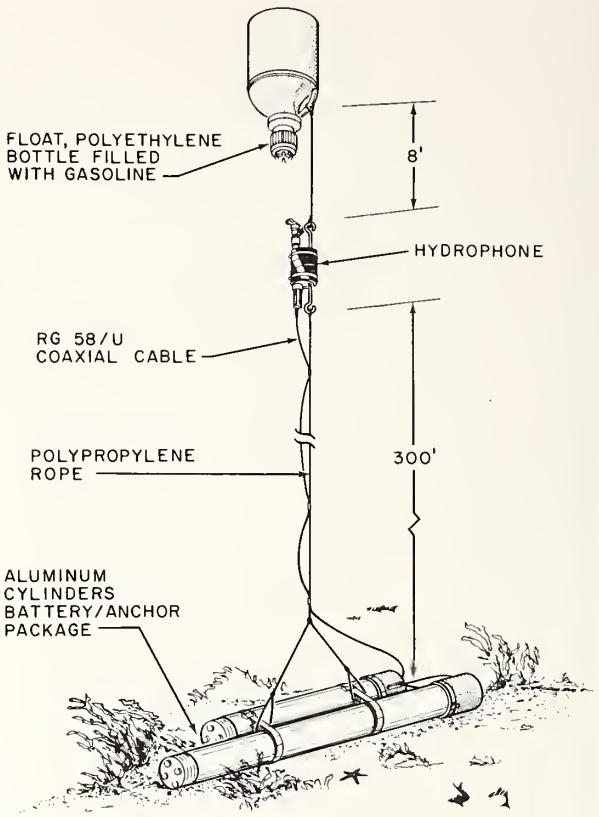

Figure 5.—MPL acoustic transponder.

particular transponder can be lost for 5 to even 15 minutes and utilized immediately upon its return. Figure 6 shows a section of recorder trace from an operation we conducted in July of this year in 4,000 meters of water about 250 nautical miles west of San Diego. Here we were tracking both the instrument package (F) and the towing ship (S) as well as recording the depth of water below the towed body on this one display.

In conducting an operation utilizing this system one makes a preliminary survey of the area using the ship's normal echo-sounding equipment. On the basis of this, one selects an appropriate configuration and an approximate location for the initial transponder drop. With the first element on the bottom, one can move off in the desired direction to a range determined from transponder one and drop number two. Number three can be placed then by navigating relative to the first two and so on. It should be emphasized, however, that the units may drift somewhat during their hour-long fall, although in most places this will be less than a half mile. In any event, the essential point is that the accurate determination of their locations is done after they are placed, using the same range data as are used for navigation purposes. This computation is most accurate if many observation points are used, although the work of computation

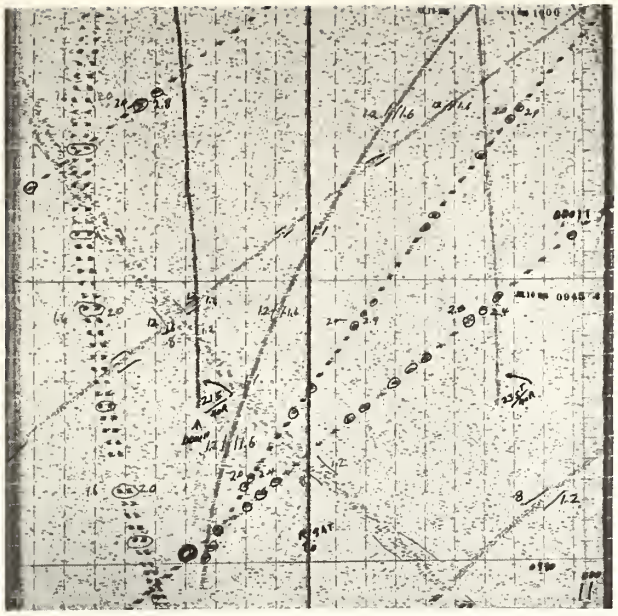

Figure 6.—GDR record showing tracking of fish and ship.

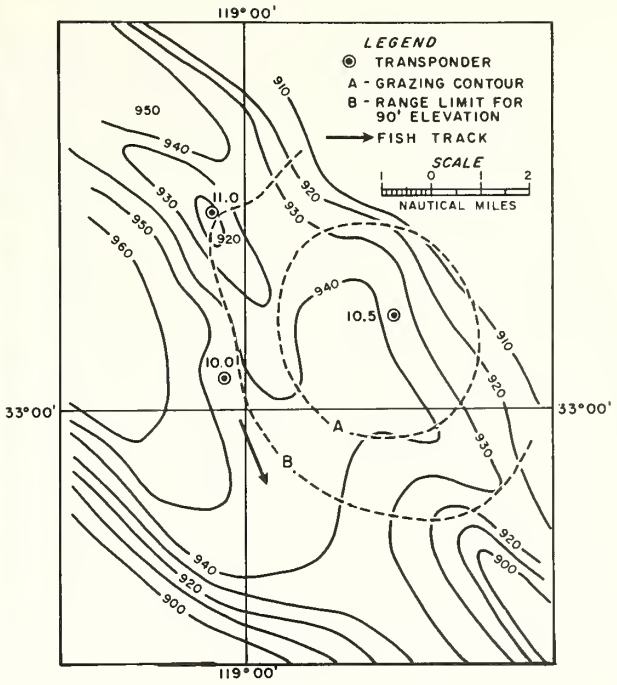

Figure 7.—Topography and range contours near San Nicolas Basin.

[Lowenstein, 1966] is then such as to make use of a digital computer desirable. A useful approach if no computer is available on board ship is to use an approximate method initially, and then carry out the detailed computation and make corrections to the track after return to the laboratory. If the surface ship can be navigated simultaneously relative to both the transponders and to some other (celestial or electromagnetic) system, it will then be possible to relate the two systems and provide an exact orientation as well as location to the self-consistent transponder system. The essential point is that high accuracy is obtained without facing the problem of accurate transponder placement which has discouraged many people from trying this technique. Accuracy is in fact achieved by survey work done after transponder placement.

A particular situation in which a set of three elements has been used by us intermittently for 8 months is shown in figure 7. This region is in the San Nicolas Basin in the continental borderland off Southern California. In this particular area we have made some preliminary acoustic investigations of the shadow cutoff as it affects useful range for near-bottom work. Because the water is nearly isothermal here, there is an upward curvature of sound rays because of increasing pressure (and thus increasing sound velocity) with depth. Over a flat sea floor, with the transponder-transducer 100 meters above the bottom, this dictates a region as in figure 8, starting at a range of about 4 km and becoming gradually higher. We found effects such as those of figure 9 as the towed fish crossed into this zone at various depths compatible with the topography and the circular paths of the limiting rays.

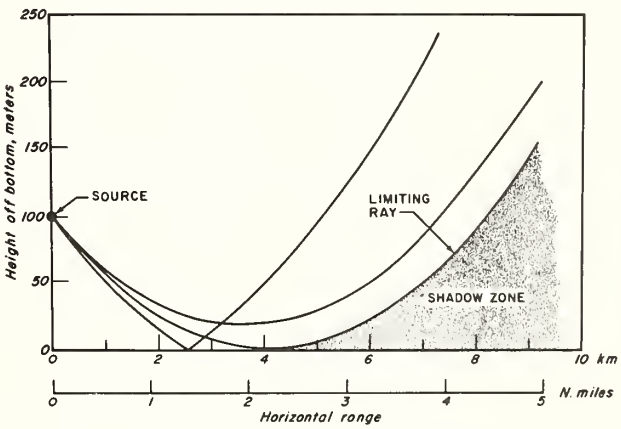

Figure 8.—Upward-refracted rays from a near-bottom source.

In a more recently placed transponder field, sufficient data have been gathered to allow an accurate analysis of the positional errors. Using 460 instances in which ranges from the instrument to all three transponders were simultaneously read from the records, and the fish was deeper than 2 km, it was possible to carry out the transponder location calculation, and from this to determine the root mean square difference between the observed ranges and the best fitting calculated position in each instance. A personal communication from J. D. Mudie stated that the resulting number was 3 meters, which is the same magnitude as several sources of error neglected

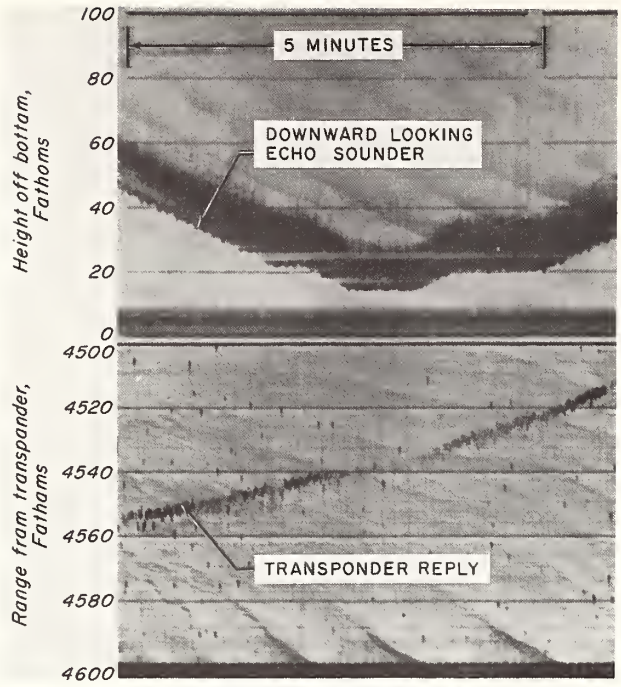

Figure 9.—PGR record.

in our computations (such as, transponder answering delay, and motion of the fish between transmission and reception of signal).

A translation of these range accuracy numbers into position accuracy [Lowenstein and Mudie, 1966] shows a mean positon error of 5 meters radius. The individual position errors are 2 to 20 meters, varying with location in the transponder field. Figure 10 shows the best computed track as plotted by the computer and figure 11 displays an expanded portion of this showing about a 5-km by 5-km region including transponder number two.

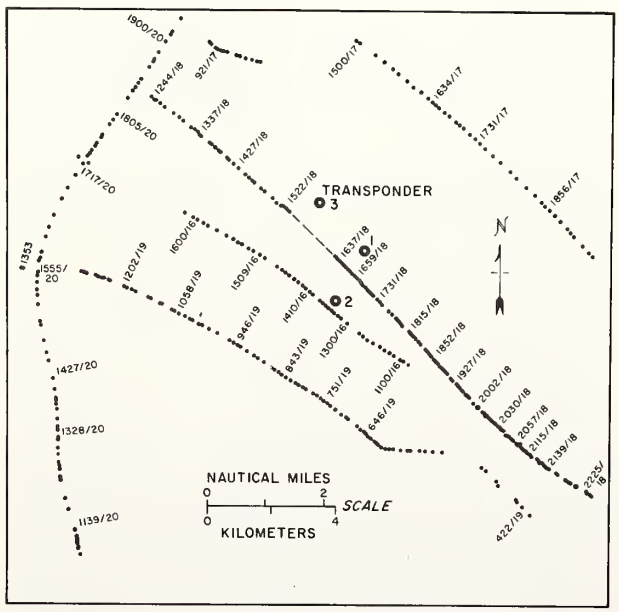

Figure 10.—Typical MPL transponder record, 6 tracks computerized record, OCONOSTOTA, April 1966.

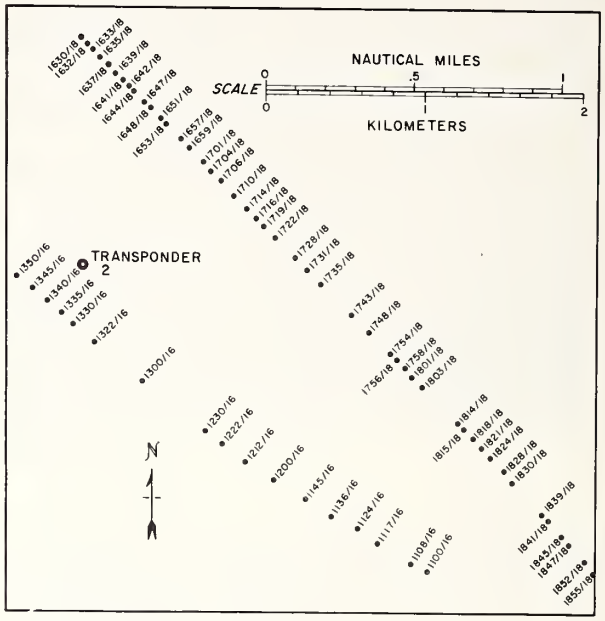

Figure 11.—Computer plot blow-up of 2 tracks for OCONOSTOTA operation of April 1966.

In addition to the random errors associated with the timing data there are systematic errors associated with the value of the sound speed used, and possible motion of the transponder hydrophones in near-bottom currents. The former, at the depths in which we are working, can be considered as a simple scale assignment which can be based to a few parts in 10^4 on sound speeds computed from available hydrographic data. If the tracking of a near-surface craft is to be done, then measurements of sound velocity (or temperature and salinity) must be made as a function of depth in the near-surface water throughout the survey. Travel times must be corrected accordingly. Currents at these depths may displace the hydrophones a few meters but more than that is unlikely. A program is being initiated to observe near-bottom currents in this area.

CONCLUSION

It appears that acoustic navigation utilizing transponders can be conducted with an uncertainty of only 5 meters over appreciable areas of the deep sea floor if adequate numbers of units are used. Systems of this sort can be set up rapidly and are useful for detailed research surveys and for search operations, as long as only a small number of vehicles are operating in the area at any one time.

While quite a variety of new systems can be visualized there are two components which should be given emphasis for future development. One of these is an inexpensive pinger with an accurate enough time base to keep drift of transmission time to less than one millisecond per day (say one part in 10^8). The other is a pressure gage accurate to one part in 10^4 of full scale where full scale corresponds to the hydrostatic pressure of 6 to 8 km of water. With these components one could then assemble a system in which any number of deep operating craft could navigate safely and without mutual interference.

Even before these new elements are available, we already have the capability of producing well-controlled detailed charts of the fine-scale topography of the sea floor and of carrying out systematic search operations using acoustic transponders and interrogation systems to provide our navigational base.

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Underwater Power Sources for Marine Geodesy

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INTRODUCTION

Geodetic operations in the marine environment will require the use of many types of devices such as acoustic transponder bench marks implanted on the ocean bottom for precise position references and marker buoys. Some of these devices will operate at the bottom of the ocean, others on the surface. These devices generally require compact power sources in the 1-milliwatt to 100-watt range characterized by long life per fuel charge, zero maintenance, and reliable unattended operation. Engineering and economic analyses will reveal the optimum power source for each particular marine geodetic system. The playoffs in these analyses will be among device reliability, capital cost, and operating lifetime. The high costs of frequent access to the system for maintenance and/or replacement of the power source emphasize the value of reliable, long-life, unattended operation.

The boundless energy in the oceans has always been an attractive potential source of power. Various concepts for the extraction of power from the ocean have been advanced and developed to some extent. These include such concepts as a mechanical oscillator actuated by sea waves, bellows-type devices which utilize subsurface pressure variations, oceanic biochemical fuel cells, and thermal power plants which utilize differences in temperature at different depths in the ocean. None of these systems have developed to the point of usefulness. It is the objective of this paper to present a comparison of three well known, commercially available power sources with potential for geodetic applications: primary batteries, fuel cells, and radioisotope thermoelectric generators (RTGs).

COMPARISON OF BATTERY, FUEL CELL, AND RTG POWER SOURCES

Each of the three types of power sources selected for comparison exhibit different characteristics. Chemical primary batteries are self-contained units in which reducing and oxidizing chemicals are connected internally with an ionic conductor to produce electronic current across the external load. Their chief advantage is proven performance and availability.

Primary batteries are commercially available with a choice of types and sizes. The most popular dry cell, the LeClanche type, is the least costly. Reliable operation for 1 year can be expected. At another extreme, zinc-mercury batteries are among the most expensive, but mercury cells will yield high-quality and reliable power for at least 2 years. Zinc-copper oxide batteries have for years provided low-cost and reliable power for railway signaling. These zinc-copper oxide batteries, "Lalande cells" as they are called, last for at least 3 years, but are not commercially popular today. It is mentioned here because its 3-year life makes the Lalande cell appear to be a promising prospect for geodetic applications.

Fuel cells are similar to batteries in construction and operation but differ in that fuel can be added continuously to produce electricity. Their chief advantage is an efficiency ranging up to about 80 percent for conversion of chemical reaction energy to electrical power. The most highly developed type is probably the H_2-O_2 fuel cell. Useful lifetimes for these power sources are currently in the range of 1 year or less.

Devices of the RTG type are essentially heat engines. In these devices, the heat generated by absorption of the alpha, beta, and gamma radiation produced during radioactive decay of the fuel is converted directly to electricity. The conversion is accomplished by directing the heat through a thermoelectric material. The most common types of thermoelectric materials in use for undersea applications are lead telluride (PbTe) and bismuth telluride (BiXTe). Typical conversion efficiencies of up to about 6 percent can be realized for these materials, with overall engineering efficiencies ranging up to 4 percent for contem-

porary devices. The lifetime of electrical generators of this type appears to be limited only by the half-life of the radioisotope fuel. Since useful radioisotopes are available with half-lives ranging from several months to tens of years, theoretical device lifetimes should cover the same range. On a practical basis, and considering other components of the device, lifetimes of 5 years seem reasonable.

In order to provide a basis for selection of the most desirable type of power source for a given application, the principal characteristics of batteries, fuel cells, and RTGs were compared in figures 1 through 4. In developing these data, an attempt was made to be as practical as possible, taking into account the commercial state-of-the-art for each type of device. The performance data and operational characteristics were analyzed to arrive at a normalized value of cost, weight, and size on a per watt basis in the milliwatt to 100-watt electrical power range. Other major characteristics, such as temperature effects, power rate, power quality, realiability, efficiency, and convenience are discussed in an evaluation of the status of development of these devices.

Batteries

Two types of cells were selected for comparison: (1) the mercury cell, representative of modern, high-power-density battery technology; and (2) the Lalande cell, an old-time, low-power-density battery. The multitude of different types of battery cells available for use is likely to fall between these two in their characteristics. For example, note the properties for the LeClanche cell, the ordinary flashlight battery, included in the tabulation below. The properties of mercury cells and Lalande cells from which the characteristics displayed in the figures were derived[1] are given in table 1. Lifetime for the mercury cell was taken as 2 years; for the Lalande cell, 3 years. Lifetime for the LeClanche cell is 1 year. These values represent lifetimes achievable under conditions of low rate of power drain.

Fuel Cells

The data for the fuel cell were calculated from the specifications for a commercial H_2-O_2 fuel cell described in a GE brochure entitled "Fuel Cells Today" (no date). The significant specifications were:

	350 W	1 KW
Weight, lbs	35	70
Size, cu. in. (excluding fuel)	2,500	3,000
Fuel, H_2, lbs/KWH	0.1	0.1
Oxidant, O_2, lbs/KWH	0.8	0.8
By-product water, pints/KWH	1	1

The cost of the hydrogen fuel, $0.50/lb, was taken from Johnson.[2] Oxygen was taken as $0.03/lb. The pressure vessels to contain 10 lbs of H_2 and 80 lbs of O_2, 1 watt-year's supply, stored at 2,000 psi, were estimated to weigh 50 lbs and 25 lbs, respectively. Total pressure-vessel cost was estimated to be $500/yr-w. Capital cost for the fuel cell was assumed to be $47,500 per KW. Scaled down to 1 watt, the cost of $47.50 per watt becomes only a minor part of the capital cost, the major part being the fuel container cost. Lifetime for the fuel cell was taken as 1 year.

RTGs

The data for the RTG stem partly from the specifications for a generator being marketed by Martin Company[3] and partly from performance data on the SNAP-7 series of generators.[4] The significant specifications were:

Power output, w	25
Weight, lbs	3,000
Fuel, Sr^{90}, C	100,000
Cost, dollars (5-year power warranty)	63,230

For the comparison, the 5-year warranted power output was accepted as the lifetime for the RTG. Table 2 summarizes the characteristics of the power systems selected for comparison.

Table 1.—Properties of Selected Battery Types

	Voc	W-hr/lb	W-hr/cu.in.	Amp. hr/lb	W-hr/$
Mercury Cell	1.34	51.4	[a]4.8	38.4	[a]1-14
Lalande Cell	0.65	19.6	0.94	.....	57
LeClanche Cell	1.5	2-30	0.2-2.5	.....	2-50

[a]The lower value was used as more representative of the case leading to maximum postulated life.

[1]Norman D. Wheeler, Survey of electrochemical batteries, *Electro-Technology*, June 1963, page 68.

[2]Charles A. Johnson, Fuel Cell Status in 1963, Paper at IEEE Meeting, New York City, N.Y., January 31, 1963.

[3]*Nucleonics*, Vol. 24, No. 6, page 22, June 1966.

[4]Personal communication. S. J. Seiken, USAEC, DRDT.

Table 2.—Comparison of Characteristics of Battery, Fuel Cell, and RTG Power Sources

Device	Expected lifetime, years	Weight, lb/watt	Size, $in.^3$/watt	Cost	
				Dollars/watt-hr	Dollars/watt
RTG	5	50-200	700	0.05	2,530
Lalande	3	1,572	22,240	0.02	460
Mercury	2	340	4,370	1	17,500
Fuel Cell	1	170	2,650	0.06	560

RESULTS OF COMPARISON

Weight and Volume

The relative weight and volume of batteries, fuel cells, and RTGs, figures 1 and 2, show a similar relationship when projected to 5 years. The weight and volume of the Lalande battery increase quite rapidly as a function of lifetime. The mercury battery and the fuel cell are fairly similar and increase in weight and volume at about one-third the rate of the Lalande battery. The RTG has a fairly constant and relatively low weight and volume as a function of lifetime. The relationships defined above are for devices without a pressure-resistant container.

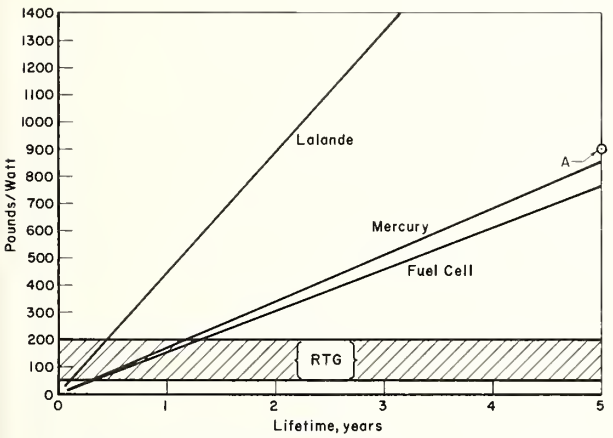

FIGURE 1.—Estimated specific weight of batteries, fuel cells, and RTGs.

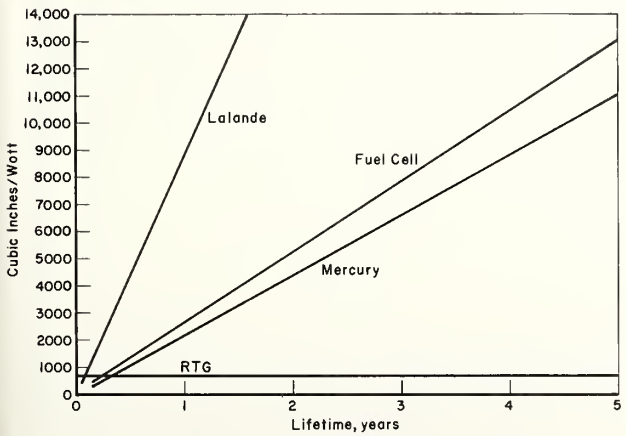

FIGURE 2.—Estimated volume per watt for batteries, fuel cells, and RTGs.

The differences will be accentuated if we consider these systems in a pressure-resistant vessel for undersea use. The accentuation in weight differences occurs because the pressure-resistant vessel weight increases at a rate greater than linear with device package size. This fact is demonstrated by comparison of Point A with the lowest level of the RTG band in figure 1. The former represents SNAP-7E, the first RTG designed for deep-ocean operation at 10,000 psi. The latter represents an advanced design, SNAP-21, for the same application. By reducing the size of the converter package in SNAP-21, overall specific weights are reduced by a factor of 18.

In general, the area between the Lalande battery line and mercury battery line represents the behavior with respect to size and weight of the family of batteries, running from low- to high-power-density systems. The fuel cell, in effect, shows the characteristics of a high-power-density battery.

The constant size and weight of the RTG system stem from the nature of the conversion process. Since the operating lifetime is short compared to the half-life, 28 years, of the postulated radioisotope, Sr^{90}, there is relatively slight difference in heat input at any time within 5 years. Thus, for a given conversion efficiency, the system size remains constant. Actual system lifetime is a function of physical, mechanical, or chemical degradation processes which may occur in the thermoelectric and other component materials. The batteries and fuel cells on the other hand which derive their power from the energy of chemical reaction can only produce more power by consuming more reactants. All other things being equal, weight and size must increase with increased life.

Based strictly on size and weight, therefore, one would choose RTGs over batteries and fuel cells if these characteristics were critical factors in a system. This conclusion is reinforced if one considers lifetimes beyond 1 year and power levels greater than 1 watt.

On the other hand, for lifetimes shorter than 1 year and possibly for power levels less than 1 watt, batteries and/or fuel cells might be the power system of choice, based strictly on size and weight.

Cost

Relative costs are depicted in terms of estimated capital costs (fig. 3) and estimated cost per watt-hour (fig. 4). The capital costs again show an increase with lifetime for the batteries and fuel cells with the RTG exhibiting a constant cost. The position of the mercury battery and the Lalande battery becomes reversed on the curves in comparison to their weight and volume behavior. Costs for the mercury cell are high and increase rapidly while Lalande cell costs are low and increase slowly. Even projected to 5 years, the Lalande battery cost is about one-third the RTG cost. The fuel cell is also relatively low cost, but as it is projected to 5 years, its cost begins to exceed that of the RTG. (Capital costs for the fuel cell include the fuel and fuel container necessary to give a postulated lifetime.) The differential between the cost of the fuel cell and the Lalande battery, and the RTG, is likely to narrow as one considers a system for operation in a pressure container. Overall costs for all systems will increase, of course, for all the proposed systems when modified for operation under pressure.

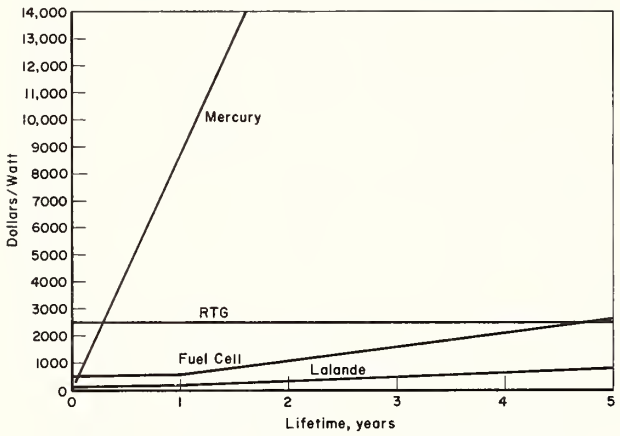

FIGURE 3.—Estimated capital costs per watt for batteries, fuel cells, and RTGs.

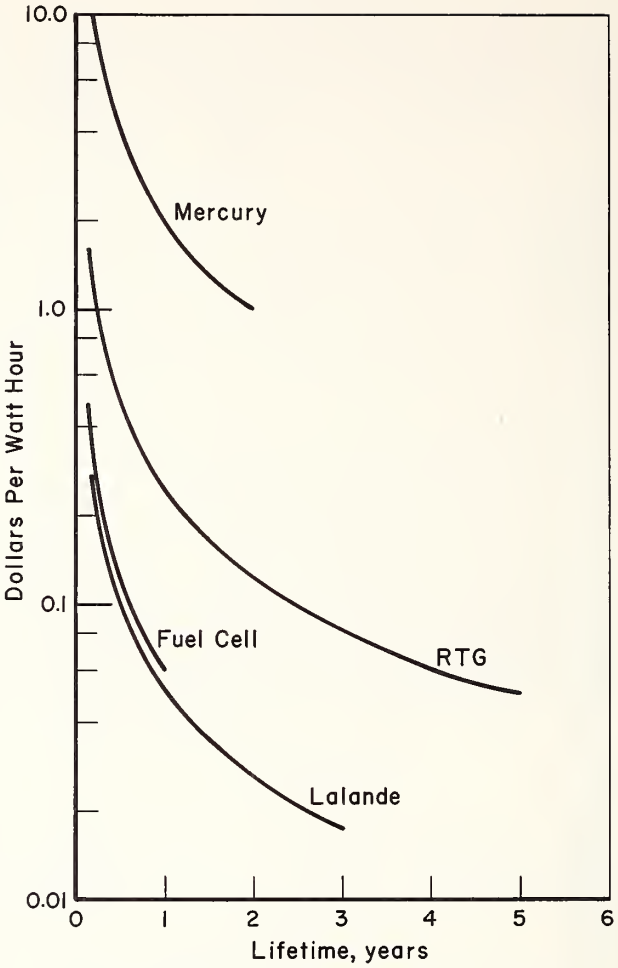

FIGURE 4.—Estimated amortization and operating costs for batteries, fuel cells, and RTGs.

Relative operating costs are considered (fig. 4) for each of the systems based on their maximum postulated lifetimes. All costs will be displaced upward on the scale if one considers an undersea system, but the degree of displacement will be least for the RTG due to its relatively small volume. Mercury cells are obviously too costly for consideration. The fuel cell and Lalande battery appear more economic than the RTG for missions of less than 1 year and 3 years, respectively. For longer missions, only the Lalande cell appears competitive, but additional emplacement costs must be considered. The size and weight of the Lalande cell, particularly for use under pressure, and for higher power levels, may also preclude its use.

OTHER FACTORS

The comparison among batteries, fuel cells, and RTGs was made primarily on the basis of size, weight, and cost as a function of lifetime. Inferences were also drawn with respect to power level as it interacts with the above factors. The presumption was "all other things being equal," these are the significant relationships. Since in real life all other things are seldom equal, we must consider some of the other factors.

Undersea Operation

We have already discussed in a general fashion the requirements for operation within a pressure-resistant container for undersea application. Let us examine the resultant constraints in more detail.

For batteries, the major effect is on weight as one places the pressure-resistant container around a relatively large package. Other complications may arise if the battery reaction yields a gas.

The same comment may be applied to fuel cells. In this case, there is a gaseous or liquid product of reaction which must be removed from the cell. Pressure operation presents some interesting possibilities, on the other hand, since gas solubilities increase with pressure leading to a potential increase in power density and smaller size, weight, and cost. Liquid hydrocarbon fuel cells offer considerable promise for reduction in costs by elimination of the requirement for a pressure vessel fuel container.

Other than the effect of pressure-resistant containment on size, weight, and cost, undersea operation places no constraint upon the performance of RTGs. Improved designs for undersea RTGs have led to a reduction in specific weight from 900 lb/w to 50 lb/w and less. Table 3 presents program objectives and development schedules for the SNAP-21 series of advanced deepsea generators.[5]

Table 3.—Snap-21 Deep-Sea Generators

Power	Fuel	Life	Weight	Schedule
10 watts.....	Sr^{90}	5 yrs	500 lbs	Fabrication initiated FY-66. Operational testing FY-67.
20 watts.....	Sr^{90}	5 yrs	700 lbs	Fabrication FY-67. Operational testing FY-68.
60 watts.....	Sr^{90}	5 yrs	1,000 lbs	Fabrication FY-67. Operational testing FY-68.

Design pressure: 10,000 psi.

Projected applications: Navigational aids, seismological stations, oceanographic research, hydrophone amplifiers.

Temperature

Batteries and fuel cells are quite sensitive to temperature of operation. As the temperature drops below a specific minimum for each type, efficiency and power density may drop markedly. For this reason, careful consideration must be given to the water temperatures in which the power sources must operate. Generally speaking, RTGs are not subject to this constraint. At lower temperatures, efficiency may actually increase because of the greater temperature span on the thermoelectric converter.

Reliability

Only in the case of the batteries are the designated lifetimes based upon statistical experience in practice. For the fuel cells, spectacular success has been achieved recently for periods to 336 hours in space flight. This performance is undoubtedly backed by operation of prototype units in the laboratory for several thousand hours. The 1-year lifetime postulated is still a development goal. Several difficult technical problems must be solved before we can anticipate extending fuel-cell life to even longer periods.

The major source of performance data for the RTGs stems from the SNAP-7 development program of the AEC, table 4. Six prototype generators were built, tested, and operated for periods of time up to 2 years or more.[6] Some of these were pulled off test for examination and evaluation before their useful life had ended. The postulated 5-year lifetime, therefore, seems reasonable but remains to be demonstrated in the field.

[5]Under development by USAEC-DRDT, personal communication, S. J. Seiken.

[6]Personal communication. S. J. Seiken, USAEC-DRDT.

Table 4.—SNAP-7 Terrestrial and Marine Strontium-90 Isotopic Power Systems

Designation	Power	Use	Date of installation	Status (February 1966)
SNAP-7A....	10 watts	U.S. Coast Guard Buoy, Curtis Bay, Md.	Jan. 1964	Decrease in output performance has stabilized at 6 watts.
SNAP-7B.....	60 watts	U.S. Coast Guard Lighthouse, Chesapeake Bay, Md.	May 1964	Performance stable.
SNAP-7C.....	10 watts	U.S. Navy Weather Station, Antarctica.	Feb. 1962	Established record for unattended Antarctica weather station operation.
SNAP-7D.....	60 watts	U.S. Navy Nomad Weather Station, Located in center of Gulf of Mexico.	June 1964	System successfully withstood Hurricanes Hilda and Betsy; performance stable.
SNAP-7E.....	7.5 watts	U.S. Navy Acoustic Beacon, Atlantic Ocean, 750 miles east of Jacksonville, Fla.	July 1964	System operation satisfactory.
SNAP-7F.....	60 watts	Offshore Oil Platform, Gulf of Mexico.	June 1965	System operation satisfactory for 6 months; subsequent power loss, unit being examined.

SUMMARY

Batteries, fuel cells, and RTGs have been compared as power devices for marine geodetic applications. Certain basic relationships of size, weight, and cost of these devices as a function of lifetime have been demonstrated. From the power systems selected for comparison, it appears that RTGs may be the optimum power source for mission lifetimes beyond 1 to 2 years. RTGs also appear to be optimum in the upper power levels considered from watts to one-hundred watts. For mission times less than 1 year, and at the lower power levels, ranging to milliwatts, batteries may be optimum. Fuel cells may generally be considered as a type of battery for this application.

Specific choices should only be made, however, after an engineering and economic analysis of the particular system.

Shore-Based Electronic Systems for Marine Geodesy

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Among the many shore-based navigation systems in use today, only a few are suitable for marine geodetic surveying in ranges beyond the line of sight. This would be the region about 25 to 200 miles offshore. Suitable systems are: Hi-Fix, Lambda, Lorac, Rana, Raydist, and Toran.

These systems are similar in that they all use the principle of measurement by phase comparison. In such a system there is either a fixed or a known phase relationship between radio waves radiated by the two stations. This relationship can be pictured as a pattern of imaginary lines of position covering the area between and around the two stations. The surveyor, by measuring the phase relationship of the two shore-based transmitters' frequencies received on the ship, can determine a line of position. A second pair of similar shore-based stations result in an intersecting line of position. They also use essentially the same operating frequencies and have comparable accuracy and operating features.

There are differences between the systems. The unique features for each system of interest to the surveyor are described in alphabetic order.

HI-FIX

This system is manufactured in the United States by the General Precision Decca Co. A main feature is that Hi-Fix uses only one radio frequency. In the usual phase comparison system, a number of radio frequencies are used (3 or more) and at times the desired frequencies, particularly those which are harmonically related, are not readily available. Statistically, there is less chance for interference on one frequency than on several, which should result in longer consistent operation. Also, greater system accuracies result from a single frequency because of less chance for differential effects present with multiple frequency operation.

Also, in common with Raydist, this system is designed to operate either in the two-range or in the hyperbolic mode. In the hyperbolic mode, the Master and the two Slave stations are located ashore and the radiation pattern is a group of hyperbolas. In the two-range mode, the Master is located on board ship and the pattern is in the form of concentric circles radiating from each of the two Slave stations. Theoretically, any of the six systems can be operated in either mode, but only the two cited are specifically designed for this dual purpose.

Another feature that Hi-Fix shares with Raydist and Toran is that the system is designed for portable operation. This means that the equipment is relatively lightweight, is placed in weathertight cabinets, and can be operated from storage batteries.

A most serious problem with any phase comparison system is the inability to identify which lane you are located in. The Hi-Fix system indicates the fractional part of the lane (or phase) the ship is occupying. There has to be some other method of identifying the lanes. If two Hi-Fix systems are used adjacent to each other, each can be used independently by separate users, and yet the other system can be tuned in to obtain much wider lanes which assist in lane identification. The dual system is called the Hi-Fix B system.

LAMBDA

This system, also manufactured by the General Precision Decca Co., is quite similar to Hi-Fix in many respects. As its name implies (*L*ow *AMB*iguity *D*ecc*A*) its unique feature is that this system has built-in lane identification operating continuously. With the exception of Rana (which is essentially three systems tied together) the other systems require separate equipment to resolve lane ambiguity and the information is not readily available.

Because of the lower measurement frequency, the lane widths of the Lambda system are about 1,000 feet while the average widths for the other systems are about 250 feet at the baseline. The

fractional parts of the 1,000-foot lanes are shown on the first set of indicators; on the second set are shown the medium lanes, which are about 4,000 feet wide. If, because of power failure or interference, there is a momentary loss in position information, the surveyor can obtain his approximate position from the second set of indicators, and then obtain the exact position from the first set. If he is unable to resolve his position within the 4,000-foot lanes, then by pressing a button an extra pointer on the second set of indicators will show the surveyor where he is located within lanes that are about five miles wide.

Lambda also has the greatest coverage of any of the six systems. The others have a nominal range of about 150 miles whereas Lambda has been carried out consistently to 500 miles by the Canadians who are using additional transmitter power and larger antennas. The greater range is due to the lower frequency. Lambda operates at about 140 kilohertz or approximately one-tenth of the frequency used by the other systems. While lower frequency offers greater range, there is a corresponding loss in resolution. In the Lambda system, this loss in resolution is not serious enough to degrade the accuracy beyond the usable limits.

For higher reliability in operation, Lambda is designed for duplicated equipment use. The two systems, the operating and the standby units, are wired/cabled together and operated as a single unit. If at any time, at either the Master on board ship or at any of the two Slave stations, there is failure or difficulty, the operator can switch to the standby unit at his station by merely pressing a button and the standby unit takes over without any change or jump in phase information.

LORAC

This equipment is manufactured by the Seismograph Service Corp. of Tulsa, Okla., and is widely used along the Gulf of Mexico where the company has established a series of permanent chains. The corporation can furnish equipment, ships, and technical assistance. Of the five systems that operate in the 2 megahertz band, Lorac offers the highest powered transmitters, 500 watts input compared to the average of 100 watts for the other systems. If all other considerations are the same, the increased power should result in range and more reliable operation. Similar to General Precision Decca Co., Seismograph Service Corp., is primarily a service organization and will either sell or lease equipment and services on a worldwide basis.

RANA

This survey equipment was built for the French Hydrographic Service and its unique feature is the ability to maintain lane identification under difficult conditions. This is accomplished by transmitting the fine, medium, and coarse lane patterns continuously. The three lane patterns, which are fed to their respective indicators, are geared together. Consequently, if a burst of static or interference occurs on any one frequency, the indicator dial on this channel could not turn violently since its movement would be restricted by the gearing to the other two phase indicators. The chief problem is that eight radio frequencies are required.

RAYDIST

This is an electronic system manufactured by the Hasting-Raydist Co. of Hampton, Va. It has several unique features:

1. It is capable of multiparty operation in the two-range mode. In this mode, the Master station is located on the ship and, as a result, the system can not be used by any other ships at the same time. By using special filters and having the Master stations' frequencies relatively close to each other, the Raydist system is capable of permitting two or three users at the same time with a single pair of slave stations, with all users being in the two-range mode of operation.
2. The Raydist system (transistorized version) has the lightest shipboard equipment, the total weight being less than 60 lbs. This figure does not include the shipboard antenna, which can be a lightweight whip.
3. Another feature is that this system has the highest resolution because the measurement frequency is twice that of the other systems, thus making the lane width 150 feet for a frequency of 3.3 megahertz as compared to the other systems' 250 to 300 feet.
4. The combination of the higher frequency, plus the fact that the radio waves are continuous (not pulsed), makes Raydist the most sensitive of any system to small motions. The rolling of the ship can be seen on the indicator dials.

Similar to General Precision Decca Co. and Seismograph Service Corp., Hasting-Raydist Co. offers a group of peripheral equipment and will provide services and assistance as described.

TORAN

This is an electronic system manufactured in France. It is unique in that the system is designed and built in pairs of Master and Slave. That is, any one group of equipment contains the Master, the Slave, and the reference station equipment. Therefore, each pair and its resulting base line are independent of any other pair and their baselines. Obviously, to obtain a position, a minimum of two pairs is needed (fig. 1), but three pairs can be used to obtain greater fixing accuracy or per-

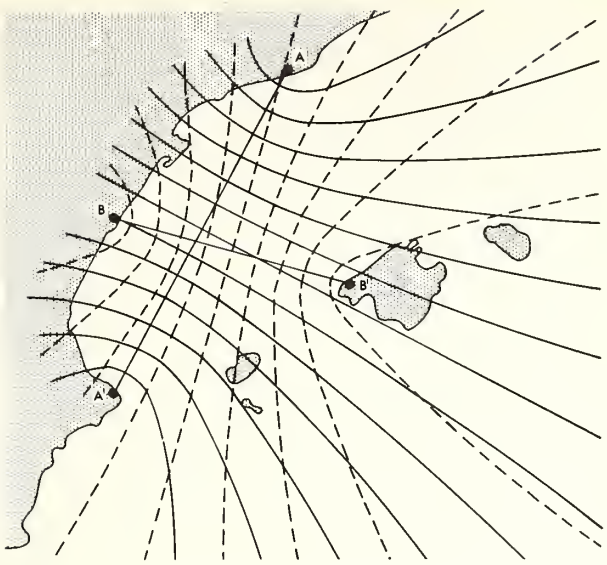

FIGURE 1.—Toran pattern.

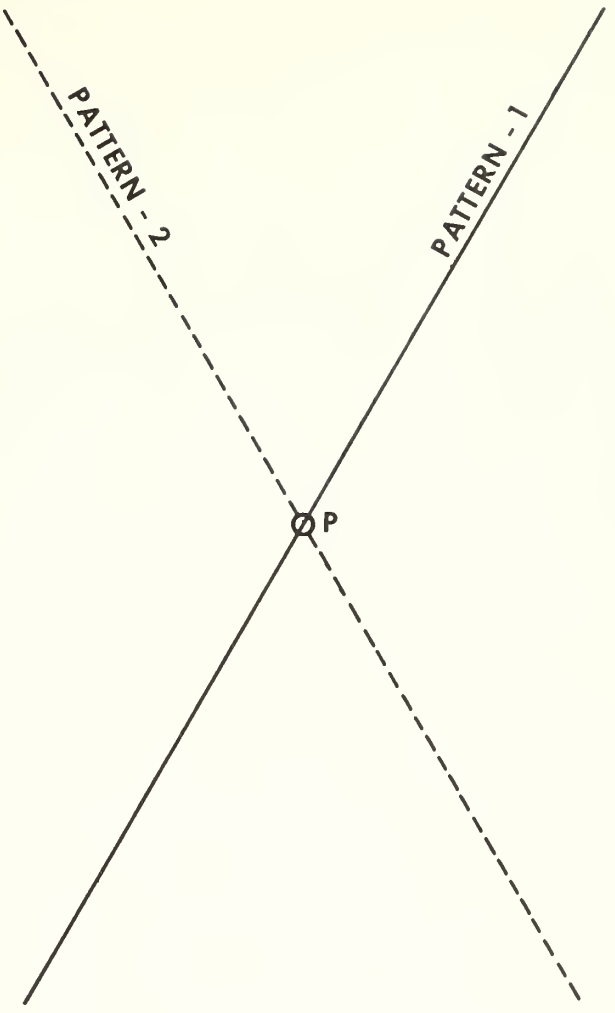

FIGURE 2.—Ideal fix.

mit leapfrogging of pairs of stations as the survey work progresses along a given area. Toran is designed for portable use and therefore is lightweight and packed in weathertight containers and can be operated from batteries.

In the discussion of the various electronic systems, I have made no mention of their accuracy. I purposely omitted the figure of accuracy usually given by manufacturers because it is meaningless. This is so because many external factors affect the overall accuracy of determining the geodetic position of an underwater marker. With any of the above systems, using ordinary care, you may expect to locate your marker to within 100 feet at 100 miles from your shore stations. If this is not good enough, by paying particular attention to the details which I will discuss below, you should be able to approach an accuracy of about 50 feet. Theoretically, you should be able to determine the position to within 5 or 10 feet, which happens to be the resolution of the systems. How close you approach this ultimate accuracy depends upon the care taken to resolve all the factors which decrease the overall accuracy.

These factors include distortion in the radiation pattern, calibration errors, nonlinearity in the measurement circuitry, random errors, repeatability of the system, instrumental errors, geometry of the radiation pattern, and the uncertainty of the propagation velocity of radio waves. The last two factors, namely the geometry of the system and the variation in propagation velocity, cause the greatest loss in accuracy.

The geometry involves the angle of intersection between the lines of position. As shown in figure 2, the method of determining the position is to plot the two lines of position values from the electronic survey equipment. From the intersection of these two lines, the position of the underwater marker can be determined. However, this is not an accurate representation. The two position values are not absolute, but represent the approximate values as shown in figure 3. In any system, there are certain unresolvable errors which cause a spread in the readings. Therefore, the true line of position should be considered to be within a band, as shown by the dashed lines on either side of the solid line in figure 3. The diamondshaped figure formed by the dashed lines represents the area within which the marker can be located. Since we should always consider the worse possible case, the distance represented by the arrows from the center to the corner of the diamond is the probable error in the determination of our marker. It can be seen that if the angle of intersection between the two patterns becomes smaller, then the arrow becomes progressively longer and hence our positional error increases. As an example, consider a hyperbolic system where, at 100 miles, the average lane width would be about 1,000 feet. Although the

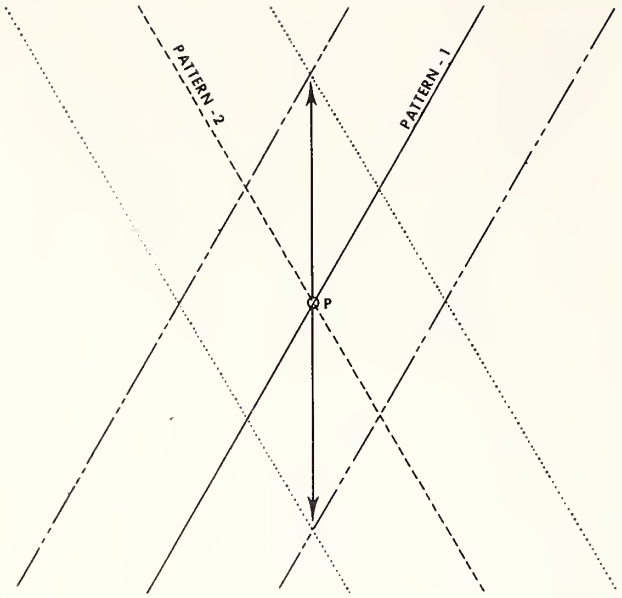

FIGURE 3.—Typical fix.

instrument can be read to the nearest .01 lane, we should consider the position to be within .03 lane to allow for the distortion and instability in the pattern, reading errors, and other residual errors. Therefore, in the above case, ± .03 lane would represent a distance of ± 30 feet. Assume that the angle of intersection between the two position values is 30 degrees. Then the length of the arrow would represent a distance of over 100 feet, or the positional error could be over 100 feet. In addition to this figure of error, there should be added all other errors, calibration, velocity, etc., which will make this figure still larger. To minimize geometry errors, the shore stations should be placed in such a position that the patterns form right angle intersection in the desired area.

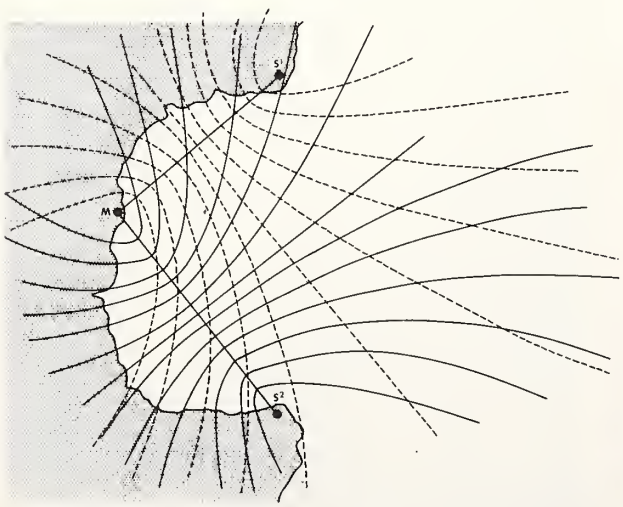

FIGURE 4.—Hyperbolic pattern 90° baseline.

Figure 4 represents a site configuration that would give the strongest position coverage over an extended area for a hyperbolic system. This is a configuration where the angle between the two baselines is about 90 degrees. In figure 5 we can see that there is much less coverage with good intersection angles when the baselines are about 180 degrees, or placed along a straight shoreline. In the case of a straight shoreline, to obtain the necessary accuracy at a distance, it

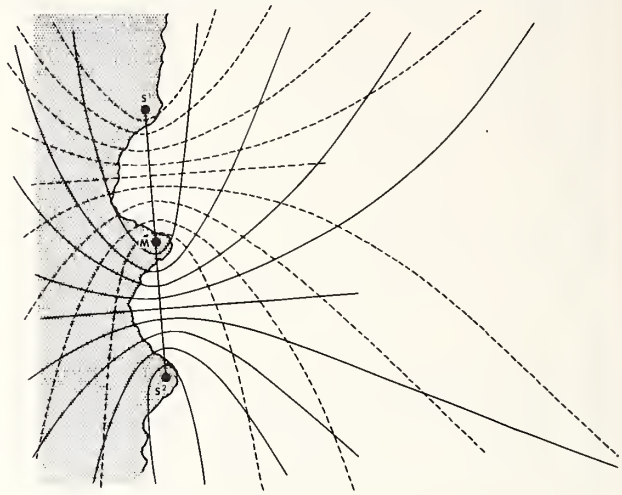

FIGURE 5.—Hyperbolic pattern 180° baseline.

is necessary to use the two-range mode of operation where the pattern is in a series of concentric circles about each Slave station. Note that in figure 6 the positions are quite strong, or have essentially right angle intersection for some distances from the two Slave stations.

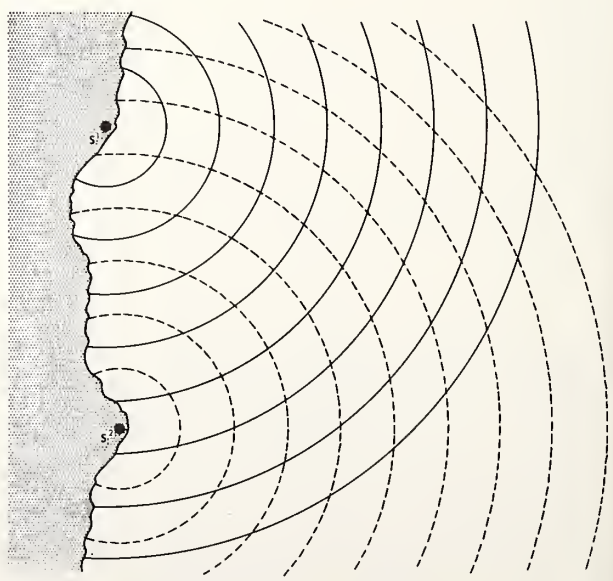

FIGURE 6.—Circular pattern, 2-range mode.

Another advantage with the two-range mode of operation is that the lane widths are a constant value and do not expand with increasing distance as is true with the hyperbolic system. That is, the lane widths at 100 miles would still remain the same as at the baseline, which is 250 feet for the usual system. This is not true with the hyperbolic system where the lane widths at this distance would be approximately 1,000 feet. The disadvantage is that with the two-range mode operation (with the exception of Raydist) is limited to a single party.

As mentioned earlier, the second source of error is the uncertainty of the propagation velocity of radio waves. The principle of distance measurement is based on the equation that *Distance* is equal to the *Velocity* of the radio waves multiplied by the interval of *Time* required for the radio waves to traverse the given distance. All electronic surveying equipment show time (or phase, which is related to time) interval, and if the velocity factor is a constant, then there is a linear relationship between distance and time. However, the velocity is not constant and it is severely affected by the moisture content of the atmosphere. There can be a daily variation in the velocity as much as one part in 10,000 or, to use concrete terms, at 100 miles this change in radio wave velocity would cause a change in position of about 60 feet, assuming all other factors remain unchanged. To minimize this error, the meteorological conditions between the ship and the shore stations should be ascertained. A plane with meteorological instruments could fly along the path between the ship and the shore stations. Or a monitor station located at some fixed point near the survey area could detect the changes in velocity and these variations could be used to correct shipboard indicator values.

I have now described the various electronic systems that would be satisfactory for determining the position of an underwater marker. I hope that I have provided you with some appreciation of the accuracy of these systems and the problems involved in attaining the desired accuracy. It is essential that all details be minutely examined and corrected if accurate positioning is desired. It goes without saying that experienced personnel play a large factor in the overall accuracy.

Application of Hyperbolic Radio Systems to Marine Geodesy

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ABSTRACT

Hyperbolic radio positioning systems currently in use for marine applications include Decca, Loran, and Omega. Each provides a fix area and has specific advantages and disadvantages for particular applications. This paper discusses the basic characteristics of hyperbolic systems, the features of existing systems, and recent developments in the area of Loran-D and elsewhere, which promise improved accuracy and availability of these systems for marine geodesy.

INTRODUCTION

Many types of radio navigation systems are used for position fixing in marine applications. They range through the entire electromagnetic spectrum, have varying degrees of complexity, and are designed to meet the needs of various users.

General navigation requirements for ships, away from congested shore areas, usually call for accuracies in the order of a few miles at best. These accuracies can be obtained by relatively simple navigation systems.

Marine geodesy, however, requires accurate position fixes, frequently at locations far removed from land--a requirement which taxes present capabilities of navigation systems. Of all the types of systems, the hyperbolic type appears to be best suited to the geodisist's problem.

RADIO NAVIGATION SYSTEMS

A brief review of the common systems illustrates some of the advantages of the hyperbolic systems. Other systems have severe limitations which make them unsuitable; some have too poor accuracy, some have too short range, while others do not provide continuous position information.

The systems with poor accuracy include the radio direction finder and the Consol systems, which have the inherent inaccuracies associated with angle measuring systems.

Another class of system with limited usefulness has good accuracy but short range. It includes high-frequency and line-of-sight systems, such as radar, Shoran, Lorac, and Raydist, all of which are limited to ranges in the order of 100 miles. These are all useful within their range limitations, but cannot be used over most of the ocean areas.

Potentially accurate, but providing only intermittent information, are Hiran (Shiran) and the Navy Navigation Satellite. These also require elaborate and expensive provisions to obtain accurate fix data.

Hyperbolic systems are basically wide-area coverage systems. Three long-range hyperbolic systems now in use which might have application to marine geodesy are Decca, Loran, and Omega. The different characteristics of each present both advantages and disadvantages for marine operations. This paper discusses the general characteristics of hyperbolic systems, and particularly the three just mentioned.

CHARACTERISTICS OF HYPERBOLIC SYSTEMS

Hyperbolic systems define a line of position as the time or phase difference of signals received from two widely spaced transmitters. The line, on a plane surface, of constant difference in distance from two foci is defined as a hyperbola, hence the generic name for this family of systems.

In the hyperbolic systems, two stations synchronized together radiate signals on a common radiated or derived frequency. A line of position, defined as a phase difference, has an accuracy of $\Delta\phi$ radians of the measurement frequency, where 2π radians $\lambda/2$, because of the difference measurement.

At 100 kHz, the frequency of Loran-C and the average frequency for Decca, $\lambda/2$ equals 1,500

meters. At 100 kHz 2π radians equal 10 microseconds, so that one microsecond is equivalent to 150 meters, or 500 feet displacement along the baseline between two transmitters.

Loran-C and Decca have basic instrumental accuracies in the order of approximately 0.01π, equivalent to about 25 feet on the baseline between the two stations. Omega instrumental errors will be about ten times that distance, since the wavelength is ten times as long.

Line of Position Accuracy

Away from the baseline, the hyperbolic lines diverge, so that the position error, for a given phase error, increases as the distance from the baseline increases. This is directly related to the angle to the two transmitters, ϕ, as seen at the receiver.

$$e/e_{BL} = -1/\sin\phi$$

One point that is easy to remember is at a distance of one baseline length from each station. There $2\phi = 60°$, so that $1/\sin\phi = 2$, and 1 microsecond change in time difference equals 1,000 ft in change of line of position.

Fix Accuracy

Two lines of position are needed to produce a fix. The accuracy of fix is a function of the gradient of the two lines, the crossing angle, and the correlation between the errors of the two lines. Figure 1 shows the generalized configuration for finding the r.m.s. fix error for the crossing of two lines of position. The only approximation here is the assumption that the lines of position are straight, a completely valid assumption for practically all cases. For the terms used in figure 1, the r.m.s. fix error can be found from

$$d^2_{\text{r.m.s.}} = \frac{K_x{}^2\sigma_x{}^2 + K_y{}^2\sigma_y{}^2 + 2r\cos\theta\, K_x\sigma_x K_y\sigma_y}{\sin^2\theta}$$

where $K\sigma$ = r.m.s. line of position error in distance.

r = coefficient of correlation between the errors in the L.O.P.'s.

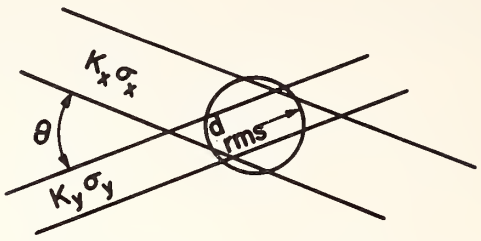
For a hyperbolic system, using a common master and two slave stations, which is the type to be considered here, the geometry is as in figure 2. Here

$$K\sigma = \frac{e_{BL}}{\sin\phi} \text{ and } \theta = \phi_1 + \phi_2$$

so that

$$d_{\text{r.m.s.}} = \frac{e_{BL}}{\sin(\phi_1+\phi_2)}\sqrt{\frac{1}{\sin^2\phi_1} + \frac{1}{\sin^2\phi_2} + \frac{2r\cos(\phi_1+\phi_2)}{\sin\phi_1\sin\phi_2}}$$

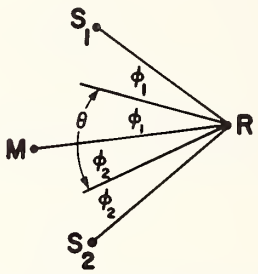
The correlation coefficient, r, is generally in the vicinity of 0.5, which simplifies the expression.



$$d^2_{rms} = \frac{K_x^2\sigma_x^2 + K_y^2\sigma^2{}_y + 2r\cos\theta\, K_x\sigma_x K_y\sigma_y}{\sin^2\theta}$$

(r = CORRELATION COEFFICIENT)

FIGURE 1.—General solution for fix error.



$$d_{rms} = \frac{e_{BL}}{\sin(\phi_1+\phi_2)}\sqrt{\frac{1}{\sin^2\phi_1} + \frac{1}{\sin^2\phi_2} + \frac{2r\cos(\phi_1+\phi_2)}{\sin\phi_1\sin\phi_2}}$$

$e_{BL} \approx 500$ ft/μSEC

$r \approx 0.5$

FIGURE 2.—Fix error for hyperbolic triad.

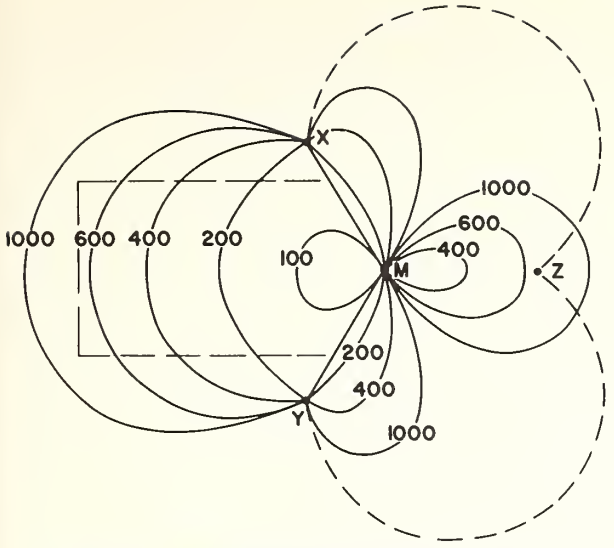


FIGURE 3.—Hyperbolic system accuracy contours in feet for 0.1 microsecond time error.

Figure 3 shows contours of fix accuracy for a three-station hyperbolic chain. Note that the accuracy degrades rapidly as the receiver moves away from the triangle formed by the stations. This points up the desirability of long baselines, so that the receiver can operate in an area of good geometric accuracy.

These contours are drawn on the assumption that the phase measurement error does not change with location, an assumption of questionable validity. This and other aspects will now be discussed relative to the various hyperbolic systems. It will be shown that the assumption of constant error is not nearly as bad as might be assumed.

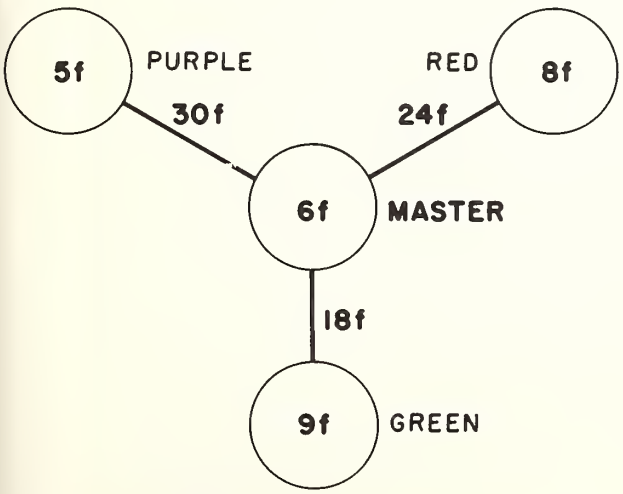


FIGURE 4.—Decca frequency relationships.

SPECIFIC HYPERBOLIC SYSTEMS

Decca

The Decca system is basically a low-frequency phase comparison system, in which separation of the stations is achieved by transmission, each on a different harmonic of a basic reference frequency. Figure 4 shows the Decca configuration.

The fundamental frequency, f, is slightly above 14 kHz, with each chain assigned a different frequency to avoid interferences. Phase measurements are made in the Decca receiver at common harmonies of the transmitted frequencies, as follows:

M operates on	$6f$ (84 + kHz)
Red Slave	$8f$ (112 + kHz)
Red phase measurement made at	$24f$ (336 + kHz)
Green Slave	$9f$ (126 + kHz)
Green phase measurement made at	$18f$ (252 + kHz)
Purple Slave	$5f$ (70 + kHz)
Purple phase measurement made at	$30f$ (420 + kHz)

Phase measurements are ambiguous every half-wavelength of the comparison frequency (because of the difference relationship). This ambiguity is reduced to a half wavelength of f (10 km) once per minute by the transmission of $5f$ and $6f$ from the master and $8f$ and $9f$ from each slave in turn, for a period of 1/2 second each.

Decca is a groundwave system. It depends on accurate phase relationships for accurate fixes. A phase error of 6° at $5f$ = 36° at $30f$. Skywaves at a level of -20 db less than the groundwave can produce a 6° error. Skywave data shows that at night, the skywave is -20 db at a range of 100 miles. Therefore, Decca baselines are limited to less than 100 miles. The geometry accuracy deteriorates rapidly at ranges of more than two baseline lengths, so even in daytime accuracy is poor beyond 200 miles.

Skywaves also have a pronounced effect on the accuracy of lane identification, since the technique of beating two high frequencies ($8f$, $9f$) to obtain a low frequency (f) introduces angular phase errors in the beat frequency the same as the errors in high frequencies.

The advantages of the Decca system are that the transmitters are relatively low power, and a short (100-300 ft) transmitting antenna can be used. For small bodies of water close to large bodies of land, such as the English Channel, Decca provides accurate fixes for the smallest investment. Existing Decca chains cover the waters off the northeast of Europe, off Newfoundland and Nova Scotia, the Persian Gulf, and the coastal waters around Bombay and Calcutta.

Omega

Omega is the ultimate in long-range area coverage systems, designed so that eight transmitting stations properly located can provide continuous navigation data over the entire earth. The extremely long baselines and multiple operation of the stations are designed to create a multiple hyperbolic grid which everywhere has excellent gradients and crossing angles.

The system operates on 10.2 kHz, with each station transmitting approximately 1 second out of 10, and a receiver measuring the relative phase of two (or more) pairs of stations. The transmission format for eight stations is shown in figure 5. This is a classless system. All stations

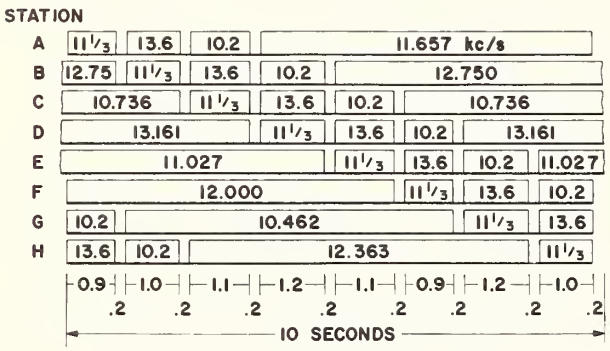


FIGURE 5.—Omega transmission sequence.

are equal. There are no master or slave stations. Comparison of any two gives a line of position. Of course, this is true of any hyperbolic system, but Decca and Loran are not instrumented in this manner.

In keeping with the classless nature of the system, synchronization of the transmitters will be achieved by concensus. This is expected to result in a system, synchronized to Universal Time, from which phase can be measured to an accuracy of about ±5 microseconds anywhere on earth.

The key to the accuracy, or lack thereof, in the Omega system, is the stability, or lack thereof, in the propagation of the 10-kHz signal. The VLF signals can be considered to be propagated in a waveguide mode between the ionosphere and earth. The effective velocity of propagation depends on the ionosphere height, and so varies from day to night, as the height of the ionosphere changes.

The propagation velocity can be considered, as a simplification, to have one value in the daytime when the ionosphere has an effective height of 70 km and a lower value at night when the ionosphere has an effective height of 90 km. Figure 6 shows the typical average variation in phase of a line-of-position measurement as well as the standard deviation observed during the period. The phase in centilanes (CEL's) which corresponds approximately to microseconds changes by over 100 from day to night. In any arbitrary position, therefore, it is necessary for an Omega receiver to include a complete almanac to determine at all times the percentage of night and day in the path to three stations located up to 4,000 miles away. The standard deviation during night and transition is about 10 CEL's (microseconds). In a typical location, at least one path will be in this "transition" condition for about 80 percent of the time. In the case of figure 6, day is 4 hours, night 4 hours, and transition 16 hours.

J. A. Pierce in his recent paper,[1] states that the r.m.s. position error at night and during transition, which is most of the time, can be ex-

[1] J. A. Pierce, Omega, *IEEE Trans.*, Vol. AES-1, No. 3, December 1965.

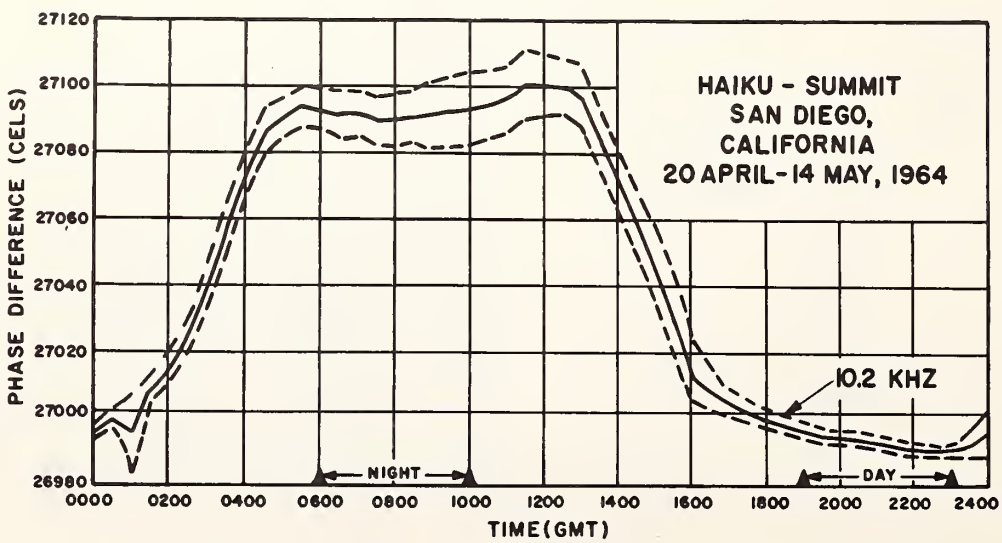


FIGURE 6.—Average diurnal variation of 10.2 kHz phase difference.

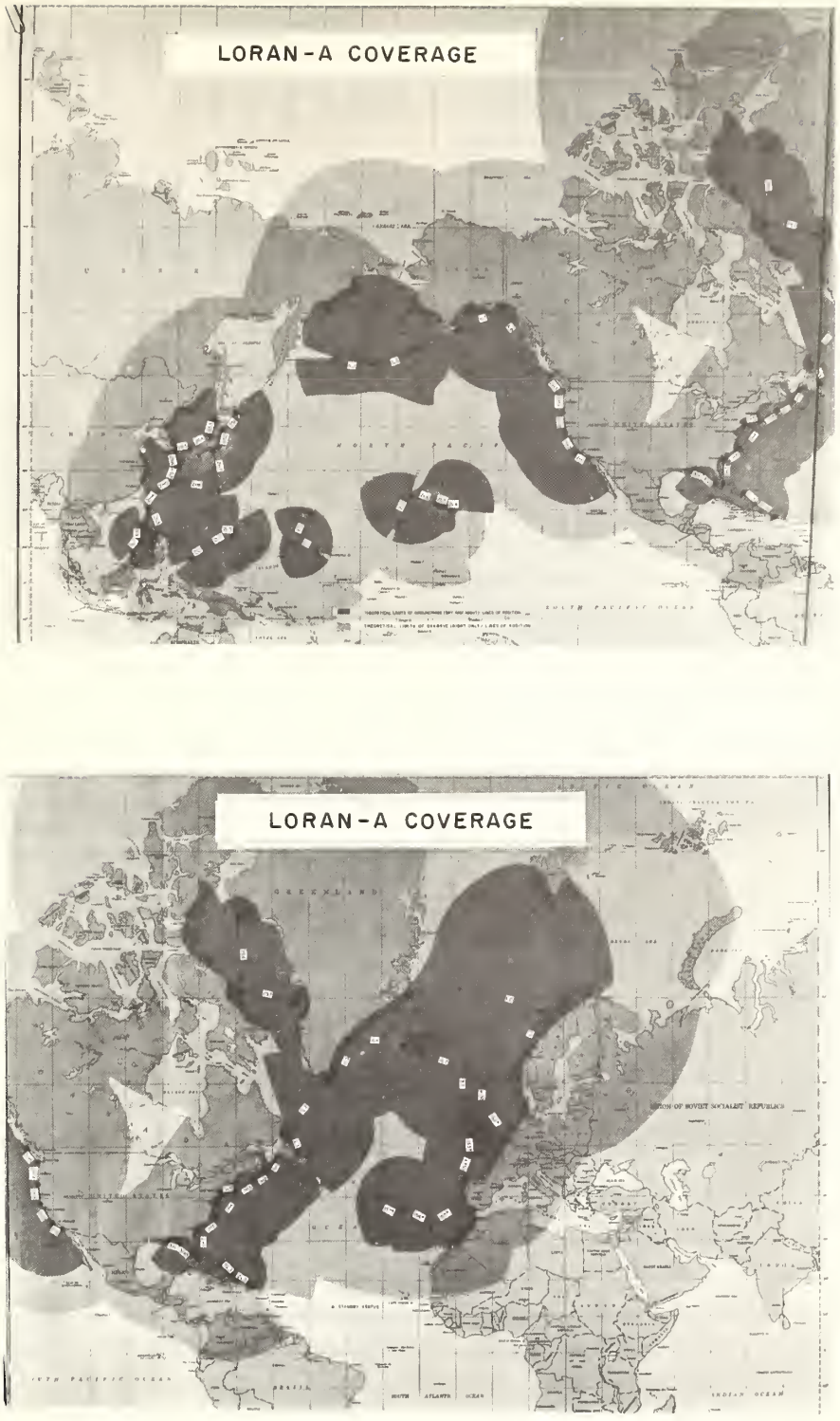


FIGURE 7.—Loran-A coverage in North Pacific (top) and North Atlantic (bottom) Oceans.

pected to be approximately 2 km. This is satisfactory for ship navigation, but hardly falls in the category of precision fixing. This does not include the effects of solar flares, which can disrupt VLF transmissions appreciably. Another point to consider is that most of the data on Omega has been taken in recent years, during the quiet period of the sunspot cycle. The number of solar flares will increase rapidly in the next 4 or 5 years, resulting in considerably poorer stability of VLF propagation. It may well be, therefore, that the Omega system will encounter appreciably greater propagation variations in the coming years than has been measured in the recent past.

It has been suggested that a nearby monitor could be utilized to improve the accuracy of Omega fixes, called "Differential Omega." During the time that the paths from a transmitter to both monitor and receiver are all daytime or all night, the monitor could provide a measure of the effective propagation velocity, and thus improve the prediction of propagation time. However, during transitions (most of the time) the situation is much more complicated, since the fraction of day and night is different for monitor and receiver, with the difference (and the period of transition) becoming greater as the physical separation increases. Recent data indicate that correlation of receiver outputs is high for separation less than 25 miles, but beyond 100 miles the correlation, and thus the accuracy of "Differential Omega" vanishes.

Loran

Two forms of Loran are in use at present, standard Loran, now called Loran-A, and Loran-C with its offspring Loran-D.

Loran-A.—The Loran-A system consists of pairs of transmitting stations radiating synchronized pulses on a carrier frequency of 1850 kHz or 1950 kHz. Receivers with conventional envelope detectors measure the difference in time of arrival of the pulses, which have a rise time of 20 microseconds and a duration of about 60 microseconds. The average accuracy of match is about 1 microsecond, corresponding to 500 feet on the baseline. Because the baselines are generally short (in the order of 200 miles) most fixes are made some distance from at least one baseline, so that the fix accuracy obtainable is generally in the order of 1-2 miles. *Loran-B,* a cycle-matching modification of Loran-A, received an abortive test several years ago. However, this concept shows promise for a medium-range high-accuracy positioning system.

Figure 7 shows the worldwide distribution of Loran-A stations, and the area they serve. Obviously their greatest utility is in the coastal waters of the North Atlantic and Pacific.

Loran-C.—Loran-C, a more recent development operates in the internationally assigned band of 90-110 kHz. In order to increase average power, and thus range, each station transmits a group of eight pulses, spaced 1,000 microseconds. Figure 8 shows the pulse pattern of a typical

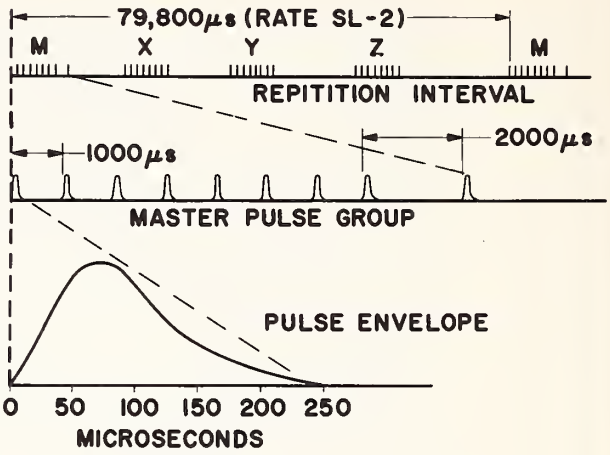


FIGURE 8.—Typical Loran-C pulses.

Loran-C chain consisting of a Master and three Slave stations, the pulse pattern of a master station, and an individual pulse envelope.

In order to permit automatic search and to prevent skywave contamination from pulse to pulse, the groups of eight pulses are phase coded, by having the phase of certain ones reversed periodically according to a specific pattern which is different for Master and Slave. Automatic searching receivers identify and synchronize to the Master and Slave stations by recognizing the phase code pattern.

The receiver measures both the delay of the pulse and the phase of the 100 kHz carrier, thus producing an unambiguous fix with the accuracy of the phase measurement, a tenth of a microsecond, more or less, depending on the circumstances. The phase measurement is made at a point halfway up on the leading edge of the pulse, which is 30 microseconds from the start. The reason for doing this is that at long range, 1,000 miles or more, the daytime skywave delay approaches 30 microseconds. A pulse measurement, to be sure of being on groundwave, must be made before the arrival of skywave, or no later than 30 microseconds after the start of the pulse.

As a result of this separation of groundwave and skywave, Loran-C achieves accurate fixes at ranges of over 1,000 miles, providing coverage over comparatively large areas. Figure 9 shows the location of the Loran-C chains now operating, and the approximate extent of the groundwave coverage from each. It is obvious that Loran-C covers much, but by no means all, of the water areas of the northern hemisphere. Within the coverage

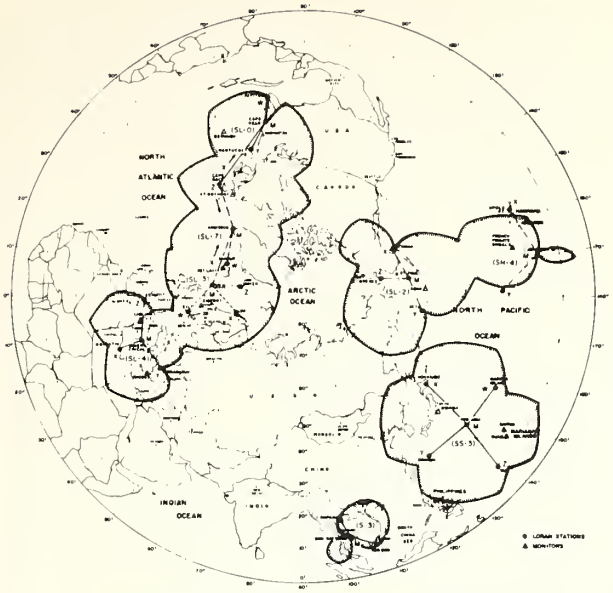


FIGURE 9.—Loran-C ground-wave coverage.

areas shown, fixes to an accuracy of 1,000 feet or better can be obtained, at any time.

SYSTEM ACCURACY

In utilizing any of the three hyperbolic systems for marine geodesy, the ultimate accuracy of each can probably be achieved because adequate time will generally be available to obtain long-time data smoothing. The errors due to noise and interference can therefore be assumed to be negligible, leaving instrumentation errors, wave propagation errors, and system synchronization errors as the factors entering into the phase measurement error at the receiver.

This means that the construction of accuracy contours, based on assuming a constant phase error at all points, is not as unreasonable an approach to the problem as it might at first appear. Instrumentation and synchronization errors will certainly be independent of position. In Decca and Loran-C propagation errors will tend to average out because of the difference form of measurement, when the paths are similar. In Omega, the propagation errors are the principal source of error, generally increasing with distance, so that moving away one station (and toward another) should keep the net error relatively constant.

FACTORS AFFECTING UTILITY

The two important factors affecting the utility of a system for marine geodesy are availability and accuracy.

The first factor, availability, is the most important. If a system is not available, it may be the most accurate in the world, but if it can't cover the area of interest, there is no sense considering it.

Decca is unable to provide accurate fixes at night more than about 100 miles from its stations, which restricts it to relatively land-locked areas, such as the English Channel, the North Sea, or the Persian Gulf. In these areas, it is already installed, and obviously is the system to use.

Omega will be a worldwide system when (and if) it is installed. The construction of each transmitting station is a major undertaking, requiring, according to Professor Pierce, an antenna system consisting of 6 miles of cable supported at an average height of over 600 feet, over a ground system several square miles in area.

Four Omega stations are now operating in an experimental net. These are at Haiku, Hawaii; Trinidad; Forestport, New York; and Norway. The experimental net covers most of the North Atlantic and North America. Commitments have not been made for additional stations at present, which means it will probably be 1970 at the earliest before any additional stations can exist.

Loran-C is operational in many areas of the North Atlantic and Pacific, with coverage as was seen in figure 9. This is of value to anyone desiring to operate in these areas, as the services are available on a continuous basis in all these areas. The accuracy obtainable can be of utility for marine geodesy, since it is appreciably better than 1,000 feet in areas with good geometric coverage.

EXTENSION OF COVERAGE

Two natural questions arise: What, if anything, can be done to extend the range of the existing Loran-C chains; and what is the feasibility and cost of installing new stations?

An obvious way to extend the coverage areas is to add another station to an existing chain, in a location to provide the desired coverage. Doing this, however, presents some problems. A typical low-power (300 kw) Loran-C station occupies some 15 acres of flat ground, may cost several million, and take up to a year to build. This is obviously not the answer for what may be a requirement for temporary coverage of a particular area, or any installation where real estate is difficult to acquire.

For the Loran-D program, development was undertaken of a portable Loran transmitting station which could be set up in small cleared areas in less than a day. This is a completely solid-state transmitter, packaged in a heli-hut for quick installation and operation, in conjunction with quick-erecting 300-foot tower antenna. This could satisfy the requirement for coverage of some specific areas, operating as part of an existing chain.

The Coast Guard has done design work on an inverted V-type antenna, which has a height of

only 100 feet, and has characteristics equivalent to the 300-foot tower. This antenna can use 100-foot wood poles, if available, or any of several types of quick-erecting 100-foot towers. It could be used where the 300-foot tower might be undesirable.

The portable transmitter with the short antenna radiates about 20 db less than a normal Loran-C station, or 3 to 5 kw peak. Over sea water, this provides useful signal out to a range of about 600 nautical miles. This can be a very useful range, however, as can be seen in the following illustra-

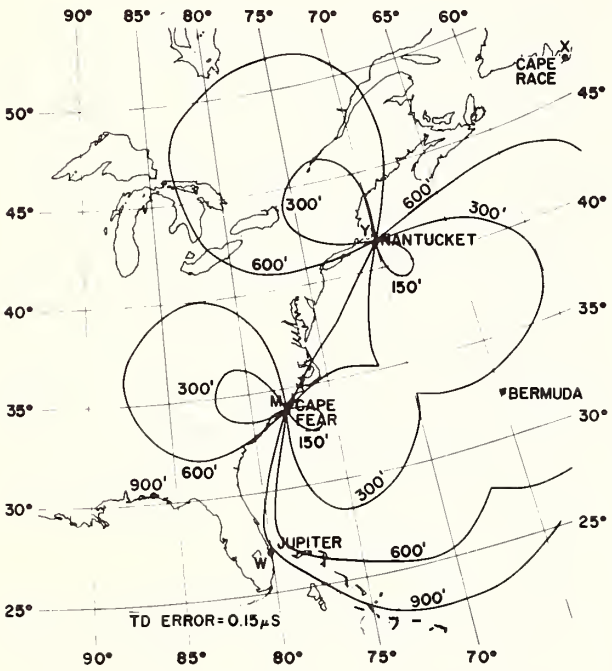


FIGURE 10.—Accuracy contours, 4-station, east coast Loran-C chain.

tion. Figure 10 shows the accuracy obtainable from the east coast Loran-C chain, as it is at present. It can be seen that the accuracy of fixes in several areas, including the Bahamas, leaves something to be desired.

Installation of an additional slave station on San Salvador would produce the accuracy contours shown in figure 11. This would add an area of high accuracy along the islands, improving the available fix accuracy by factors of two to three. The area of accurate coverage along the islands could be increased by having the new station further down the island chain, at some sacrifice of coverage along the U.S. coast.

As an alternate, a station might be set up in Bermuda. The accuracy obtainable from this configuration is shown in figure 12. A portable type station in Bermuda, with a range of 600 miles, would cover most of the area shown. A high-power station would provide even greater

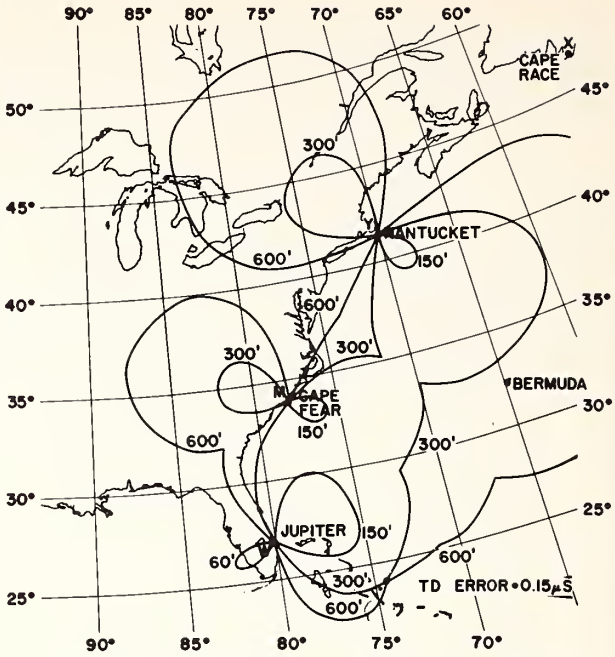


FIGURE 11.—Accuracy contours, east coast Loran-C San Salvador station.

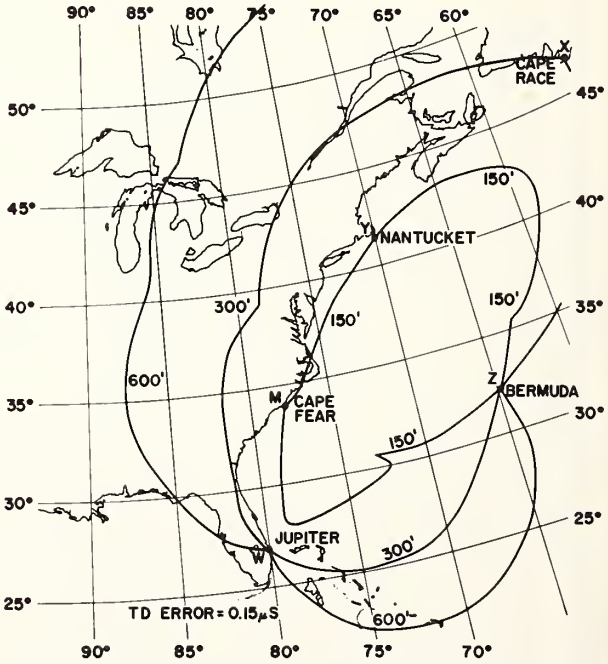


FIGURE 12.—Accuracy contours, east coast Loran-C Bermuda station.

range, usable in the Bahamas and off the coast of Canada as well.

Actually, surprising improvement in coverage of the Loran-C off the shores of the East Coast will be provided by addition of a station now under construction in Indiana, which is intended to improve the coverage over land. Figure 13 shows the accuracies which will result from the addition

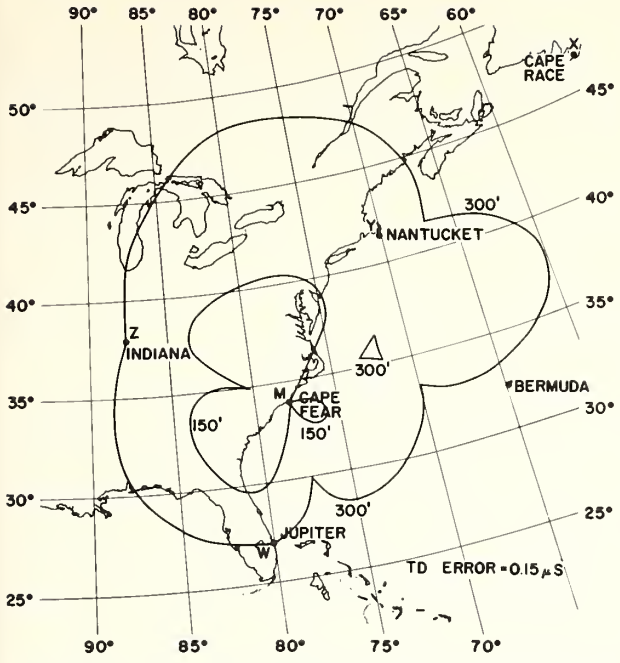


FIGURE 13.—Accuracy contours, east coast Loran-C Indiana station.

of the Indiana station to the chain, which is expected to be in operation by January 1967. Overland phase correction charts will be calculated and made available for this station by the U.S. Naval Oceanographic Office.

SUMMARY

In summary, it is apparent that all three of the hyperbolic radio navigation systems--Decca, Omega, and Loran--have varying degrees of usefulness.

Decca provides accurate position fixes with the least cost, but its short range limits it to relatively small areas so that its usefulness is limited to coastal waters.

Omega is expected eventually to cover the entire world, but at present it is limited in coverage to the North Atlantic and eastern North Pacific. The accuracy obtainable is, at best, 1 to 2 miles.

Loran-C covers a large portion of the North Atlantic and Pacific, as well as the Mediterranean, with relatively high accuracy, better than 1,000 feet. It offers the possibility of expansion to cover additional specific areas to high accuracy, even on a temporary basis, at relatively low cost.

Airborne DME Systems for Marine Geodesy

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A great deal has been said and written about Shoran in the 22 years since this blind-bombing device was adapted to geodetic surveying. For this reason I will only briefly review the historical highlights and the details of operation before going into the possibilities of marine geodetic applications. The feasibility of using Shoran as a surveying instrument was first investigated in 1944 by the 1st Photo and Mapping Group, USAAF [Laurila, 1960]. The following year a British-American team in Italy actually measured a line some 380 miles long using a Shoran-equipped aircraft [Hart, 1964]. During the same time period the U.S. Coast and Geodetic Survey ship *Explorer* ran several hundred miles of hydrographic surveys in the Aleutian chain using Shoran for position control [Burmeister, 1947]. Shortly after the end of World War II, units of the Army Air Force's 311 Reconnaissance Wing, with the assistance of Wright Air Development and Air Proving Ground elements, conducted a 3-phase test and evaluation program using two Shoran-equipped B-17s [Aslakson, 1947]. These tests proved that Shoran was acceptable in the geodetic community and led to the formation of plans for subsequent large-scale surveying projects and equipment modifications for improved accuracy. Credit must be given Captain (then Colonel) Carl I. Aslakson, USCGS (Ret.) who directed these tests as well as several survey projects which followed.

In 1949, the improved equipment, called Hiran, for *Hi*gh Precision Sho*ran*, was ready for testing and was shipped to Florida, where the Shoran phase-III tests had been run. The modifications, one of the most important being provision for manual gain control, improved the potential accuracy of single-line measurements from about 1/60,000 to better than 1/100,000 [Hunkapiller, 1955].

During this same time period, the Geodetic Survey of Canada, which also had been testing Shoran, embarked on an ambitious 6-year program to link all of Canada with a Shoran net [Canada, 1955]. By 1955, some 384 lines were measured and 92 positions established. A combination of Hiran ground stations and Shoran airborne equipment was used for this work.

Subsequently, a total of 30 U.S. Air Force aircraft, 15 RB-50s and 15 RC-130s, were equipped with Hiran and standard mapping equipment for worldwide survey projects. Some of the older aircraft are now being retired and will soon be replaced by RC-135 aircraft equipped with Shiran (S-band Hiran) [DiCarlo and others, 1964].

There are two basic methods of surveying with these airborne DME equipments: (1) the line-crossing mode, and (2) the photo-control mode. In the former the aircraft is flown at near right angles across an imaginary line between the known and unknown station. The minimum sum of the range readings from each station, after suitable corrections and reduction to the reference ellipsoid, is taken as the distance between stations. Additional lines measured to the unknown station from other known points then provide sufficient data to compute the unknown station position. In the photo-control mode, two stations on known points are interrogated to yield the aircraft position. Mapping photography is exposed simultaneously with the position measurements and the nadir points are then photogrammetrically reduced.

Hiran (Shoran) accomplishes these range measurements by determining the time it takes for an electromagnetic pulse to make the round trip from aircraft to ground station and back. The airborne set consists of a transmitter and receiver plus a recorder group. Transmission frequency is 230 and 250 Mc/s and reception is on 300 Mc/s. Two transponder ground stations are employed, one receiving the 230 Mc/s signal and the other the 250 Mc/s, but both replying, after a fixed delay, on 300 Mc/s. The transmitted signal is pulse modulated, putting out 930 pulses/second, each of 0.8 microsecond duration. The airborne set measures the time

interval between transmission and reception of each pulse and with suitable electronic hocus-pocus converts this information to distance.

Shiran, known officially as Microwave Geodetic Survey System AN/USQ-32, differs in several respects from its predecessor. It is a phase comparison system transmitting a CW carrier on 3312 Mc/s at 20 watts average power. This carrier is modulated by four ranging tones which resolve range ambiguities from 500 miles down to 0.725 foot [Salkeld, 1966].

In operation the transmitter is on continuously but a frequency synthesizer generates keying signals which interrogate up to four ground transponders sequentially at the rate of 10 times per second. The transponders reply briefly on 3087 Mc/s, each to its own particular keyed signal. The receiver demodulates each returned signal and compares the phase with that of the respective transmitted modulated signal. These phase differences are interpreted directly by an electronic phasemeter as a binary value of slant range. These binary values for each of the four coarse- to fine-modulation frequencies are then transformed by a digitizer to composite 22-bit binary range words. An operations unit displays the slant ranges from each transponder and dumps the range words on magnetic tape five times per second.

Many other current phase-locked DME systems operate with basically the same electronic principles just described. However, Shiran has one added feature, a 12-radian modulation index. In addition to providing a large data signal-to-noise ratio, this circuitry effectively reduces errors that might otherwise arise from multipath propagation. Since extremely low grazing angles are quite common in airborne DME operations, this protection was a must.

The following comparison, in which the frequency differences are self explanatory, shows the basic differences between Hiran and Shiran.

HIRAN-SHIRAN COMPARISON

	HIRAN	*SHIRAN*
Frequency.....	230-300 Mc/s	3.0-3.5 Gc/s
Calibrate.....	manual zero set	automatic
Recording.....	film strip	digital-magnetic tape
Recording rate...	1x/3 sec.	5x/sec.
Channels.....	2	4
Mode.....	pulse	CW
Resolution.....	1 + meter	0.22 meter

Proper calibration of the Hiran receiver is difficult and subject to operator skill. Calibration of both the Shiran ground and airborne units can be accomplished any time (except during range measurement) by depressing a button for 10 seconds.

The change from film strip to magnetic tape recording will reduce the time and effort required for data reduction since the tape can go directly from aircraft to computer.

The 15x increase in recording rate tends to produce a much smoother range curve, hence the minimum sum can be more accurately interpolated.

Four-station interrogation naturally increases the observation redundancy for certain types of missions and offers greater flexibility.

The pulse to CW change was made simply because phase comparison techniques have advanced to the point that the necessary accuracy can be obtained at considerable reduction in power requirements (at a given frequency).

The Hiran resolution is shown to be on the order of 1 meter. This is the theoretical resolution for the operating frequency and is actually degraded by a factor of two or three by the instrumentation and operator capability. On the other hand, the quoted 0.22 meter resolution for Shiran is built into the equipment and is not subject to operator skill.

I have not shown any accuracy comparison and cannot, simply because the absolute accuracy of Shiran has not yet been determined. Hiran, through operational experience, has demonstrated a capability for rather consistently producing proportional part accuracies on the order of 1:100,000. Preliminary flight tests were run on Shiran in 1963 and the resulting data, as analyzed by the Army Map Service [Blodgett and Masek, 1965], showed the probable error of a single measurement to be 2.5 meters. Of greater importance than the value of the probable error was the fact that, although the tests allowed 12 line crossings (standard procedure in Hiran operations), no significant change occurred in the probable error using the range values obtained with only three crossings. This indicates that Shiran has considerably greater repeatability than Hiran and will consequently speed up the airborne surveying operation for which it was designed.

Let's turn now to an examination of the marine geodetic problem, a job for which Shiran was not specifically designed, but for which it may have potential applications. The portion of the overall problem, for which airborne DME may prove useful, is that of precisely fixing the position of a ship located over a bottom transponder array, and in turn, ranging out from this position to provide continuous fix data on a cruising survey vessel.

Traditionally, a dilemma has arisen in extension of control using electronic equipment. High-frequency systems yield high accuracy but are limited to line-of-sight ranges, while low-frequency equipment, although capable of providing

signals over great distances, does not produce geodetic accuracies. The following plan for extension of control using airborne pickets is designed to extend the useful range of a high-frequency system and at the same time preserve its inherent accuracy. Note from the inset in figure 1 that the normal ground-to-air-to-ground range limit of approximately 500 n.mi. can be doubled by the addition of another aircraft. Air-to-air ranging cannot be done with the present Shiran-configured aircraft but can be achieved by the installation of a transponder in each airborne system.

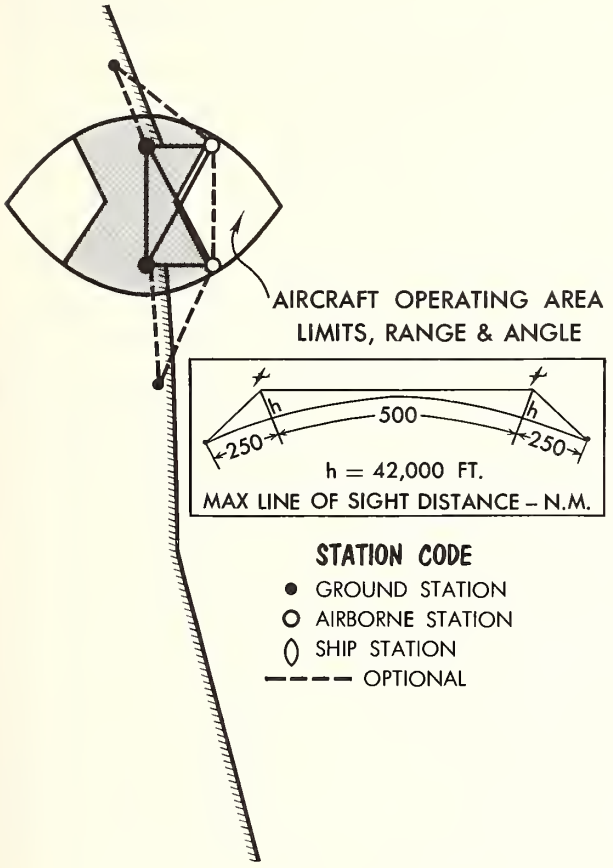

FIGURE 1.—Airborne picket parameters.

However, the employment of more than one aircraft creates a dynamic situation which rules out the conventional line crossing methods. Instead we must adopt the photo control techniques of fixing aircraft position with two or more ground stations located on known control. The outer boundary of the egg-shaped area in figure 1 denotes the range limits for an aircraft interrogating two ground stations on a nominal 200-250 n.mi. base line. The shaded area is denied the aircraft since the station angle will become less than 30° within this area, therefore creating excessive geometric dilution of precision. Anywhere within the clear area the position of an aircraft can be determined for any instant of time. The fixing of two aircraft from two ground stations, as depicted, requires a change in the transponder keying code to permit sequential interrogation from each aircraft. Actually, for the coastline departure case shown here, an extended baseline with two sets of transponders, each set servicing a different aircraft, could be utilized. As will be seen, however, the entire concept is based on the ability to fix two ship stations from two aircraft so the keying code change is a must.

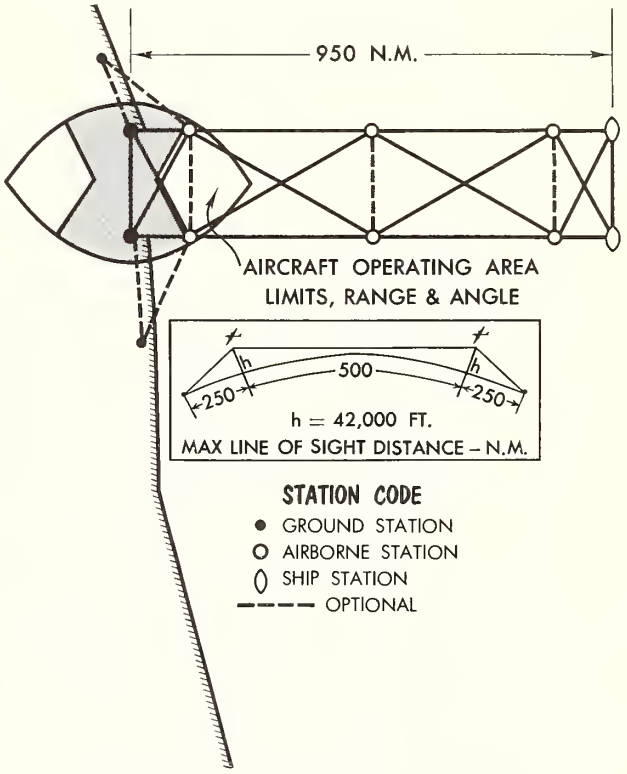

FIGURE 2.—Control extention perpendicular to base.

Figure 2 shows the airborne picket loiter pattern necessary to extend the baseline and fix the position of two ship stations located offshore at the indicated distance. It is obvious that there is a discrepancy in the distance shown in the figure 1 inset and figure 2, especially since three aircraft are now shown deployed on line between ship and shore. Figure 2 was scaled using only 225 n.mi. and 450 n.mi., respectively, between the ground-to-air and air-to-air stations since these are more realistic figures for an actual operation of this complexity. Furthermore, these maximum ranges must be taken along the diagonals of the rectangles, which in this figure add up to 1,350 n.mi., leaving us with a net gain of 950 n.mi.

There is no theoretical limit to the distance which could be bridged. The distance shown here is a probable practical limit.

Perhaps the dotted lines (indicated as optional measurements) also require an explanation since it is obvious that the accuracy would be enhanced if these ranges were read. The option amounts to another modification of the Shiran set to permit interrogation of five instead of the present limit of four transponders.

If the Shiran system is sufficiently altered to suit this purpose, what happens during the operation? There are now six aircraft orbiting in some random manner about a selected point, each reading a range on his five nearest neighbors at a rate of five times a second. This is an extremely dynamic situation. It is further complicated by the lateral movement of the ships and the wave-induced motion of each antenna whose position we are attempting to fix. The two latter problems can be dismissed by assuming: (1) that the ships' lateral motions in relation to the bottom transponders can be solved by some means as suggested by [Mourad 1965] and others at this symposium; and (2) that the wave-induced motion of each antenna can be determined by means of the ships' inertial platforms.

The overall situation can be visualized by imagining a series of photographs taken from high over the area in a balloon. Exposure time is 20 milliseconds and exposure rate is five per second. Each aircraft occupies a different position

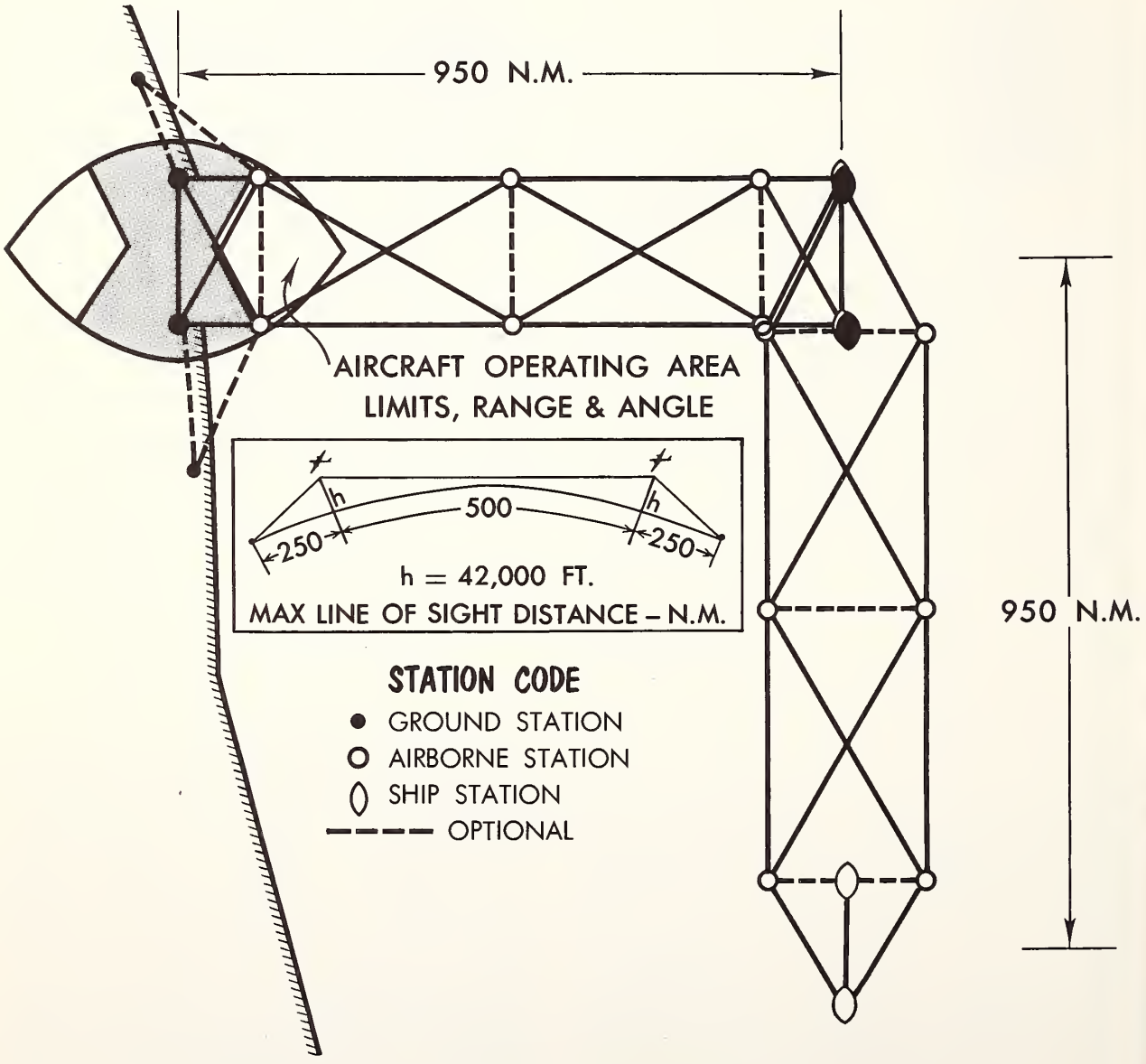

FIGURE 3.—Control extension parallel to base.

on each photograph, but photogrammetric reduction of any single picture yields the positions of each ship since each aircraft serves as a fixed control point. In the actual operation, of course, no photography is involved; time is the correlator. However dynamic the situation may appear, it happens that at each 1/5th-second interval a complete set of data is gathered containing more than enough measurements to provide a unique solution for each station position. Thus, in one hour, some 18,000 separate solutions for the positions of the two ships could be generated. This should be adequate to deal with any random errors, but any naturally occurring biases, arising from such things as unknown index-of-refraction coefficients, must be dealt with separately.

Figure 3 is identical to figure 2 except that the extension is now oriented parallel to the base line. Note that the figure is somewhat strengthened by this orientation because a longer base can be established between the airborne stations. Figure 4 indicates that the loop is to be closed.

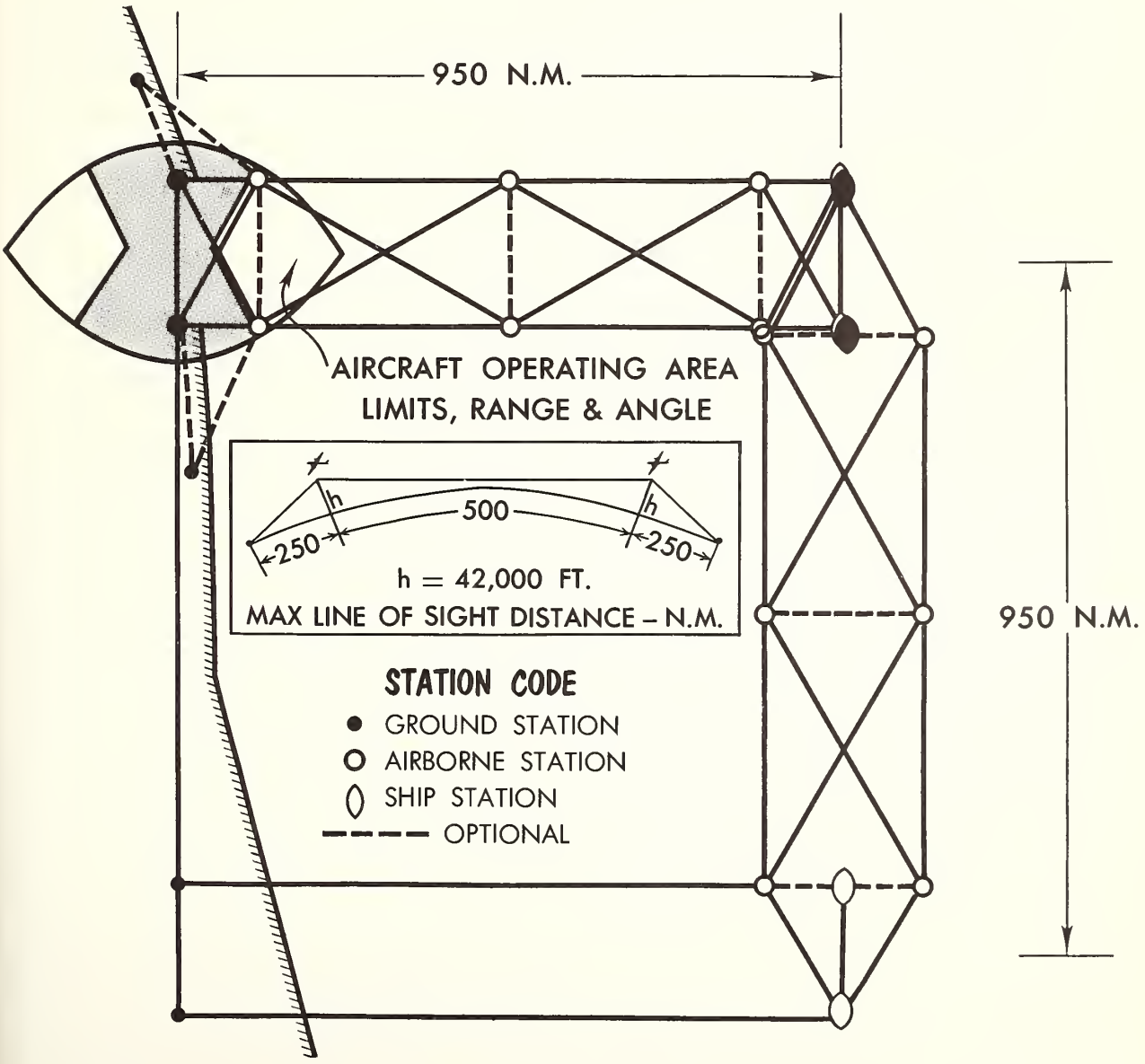

FIGURE 4.—Completed rectangle.

After establishing sets of recoverable geodetic positions some 950 n.mi. apart on the ocean bottom, can the same basic methods be used to control the position of a moving survey ship? Figure 5 shows an idealized situation with an ocean grid spacing of 950-n.mi.-squares and a pair of ship stations in the center of each. Two aircraft interrogating the two ships (each stationed over known control points) can position a survey ship anywhere within the indicated 450 by 700 n.mi. area, that is, within some 300,000 sq. mi. The addition of two more airborne pickets (fig. 6) will allow extension of control to a survey ship anywhere within the large circle, which happens to include the 950 x 950 n.mi. area assigned to this pair of geodetic control points.

Figure 7 shows an alternate plan for survey ship positioning with one airborne picket. This one aircraft flys back and forth creating a base line from which to resect to the ship. Since the ship is moving this cannot be considered true resection and depends on knowledge of the ship's speed and track to advance the range measurements to a common time. Obviously, accuracy will be degraded, but this might be permissible for some resurvey or gap-filling operations.

The idealized 950-n.mi.-spaced grid can be extended to a more practical problem, a system capable of spanning the North Atlantic Ocean (fig.8). Six and one-half ocean-station pairs, the half being paired with an island station, would provide sufficient control to conduct detailed survey operations over this entire area. Ground-based stations would, of course, be utilized for all survey operations within approximately 600 n.mi. of the mainland or island groups. It is assumed that all such potential land stations will be positioned on the World Geodetic System to the required accuracy through existing geodetic satellite programs.

Any rigorous analysis of the accuracy of establishing geodetic control or survey ship positioning by the methods presented is impossible at this time. Sufficient data is not available because the assumed modifications do not exist.

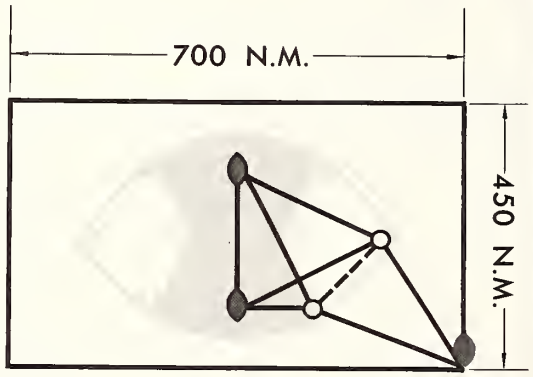

FIGURE 5.—Operating area—2 airborne and 2 ship stations.

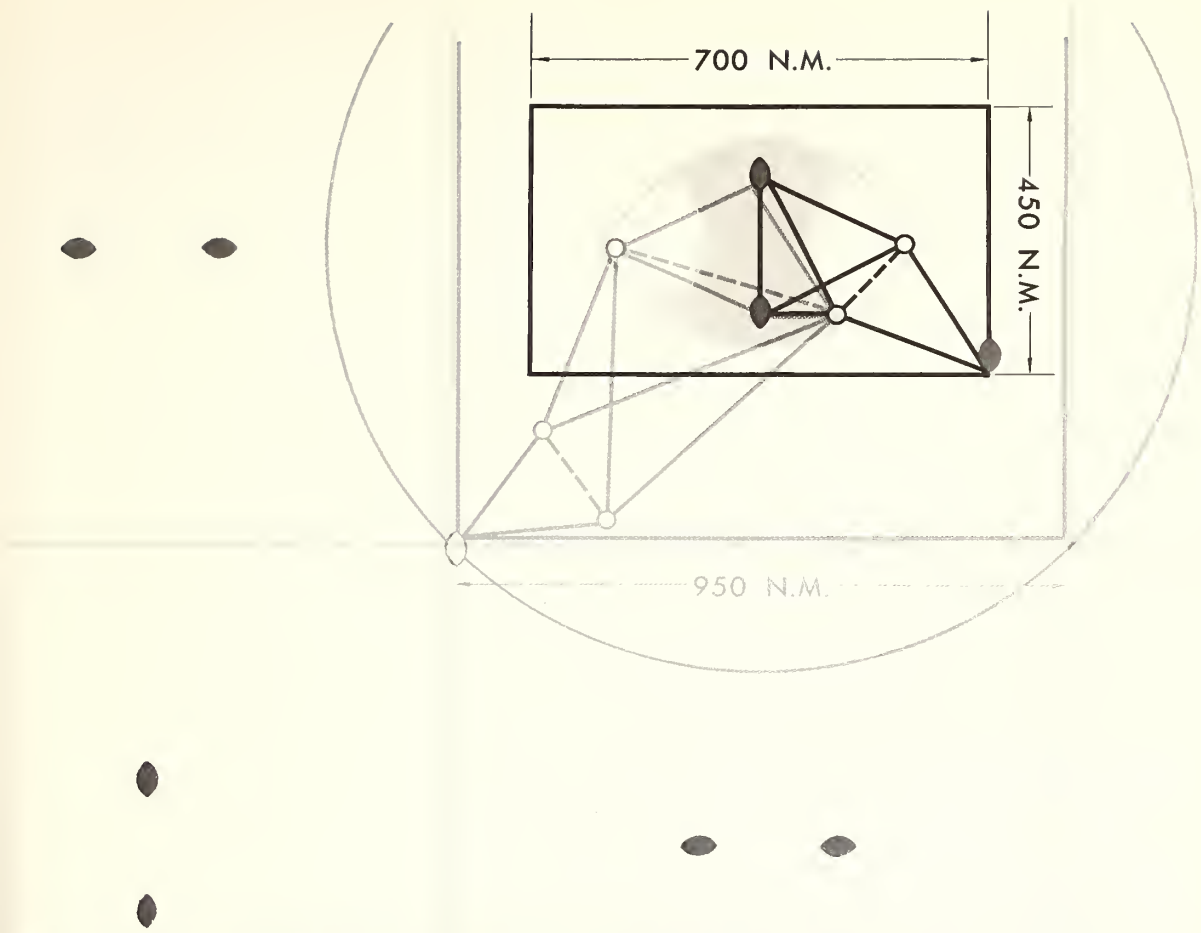

FIGURE 6.—Control area—4 airborne stations.

However, some ball-park figures can be arrived at by extrapolating from the 1963 test data. These tests showed the accuracy of photo-nadir positions to have a probable error of about 6.6 meters which includes errors induced by the photogrammetric procedures in going from aircraft to ground position. The probable error of a single line measured by the line-crossing technique was determined to be 2.5 meters. The actual aircraft position-fix accuracy should then lie somewhere between these two figures. Assume an error of 5 meters, then degrade this by a factor of two because the test data were taken with strong station angles while the extension plan involves angles nearer 30°. If this 10-meter error is propagated through the seven basic figures, there is a probable error of about 27 meters for the ship position, or better than 1:50,000 relative to the base line. Net adjustment after loop closure would go far toward improving these figures since the elliptical form of the airborne station error contributes the greatest portion of the total error. I must stress the fact that these error estimates are not to be taken as the final word, but are presented only to give some idea of the order of magnitude of the accuracy to be expected from such control extension. Additional tests with Shiran in an RC-135 aircraft, scheduled sometime in 1966, should yield data that can be more directly extrapolated into this problem.

It has already been indicated that some equipment modifications would be necessary. I would like to go one step further and suggest a complete new set of equipment and a different aircraft concept. The use of drone aircraft at the air stations shown in figure 6 would effect a much more economical operation. This is not so critical for geodetic control extension because of relatively short on-station times, but it does become quite important for survey ship control because constant surveillance is necessary. Drones are available that appear to meet most of the criteria for this operation, except the weight limitation. For instance, the Ryan Model 178 radio-relay drone can carry a 300-pound payload to 44,000 feet and remain on station for upwards of 20 hours. This weight limitation would prohibit the use of the conventional Shiran transmitter-interrogator since the console weighs about 2,000 pounds. The Shiran manufacturer,

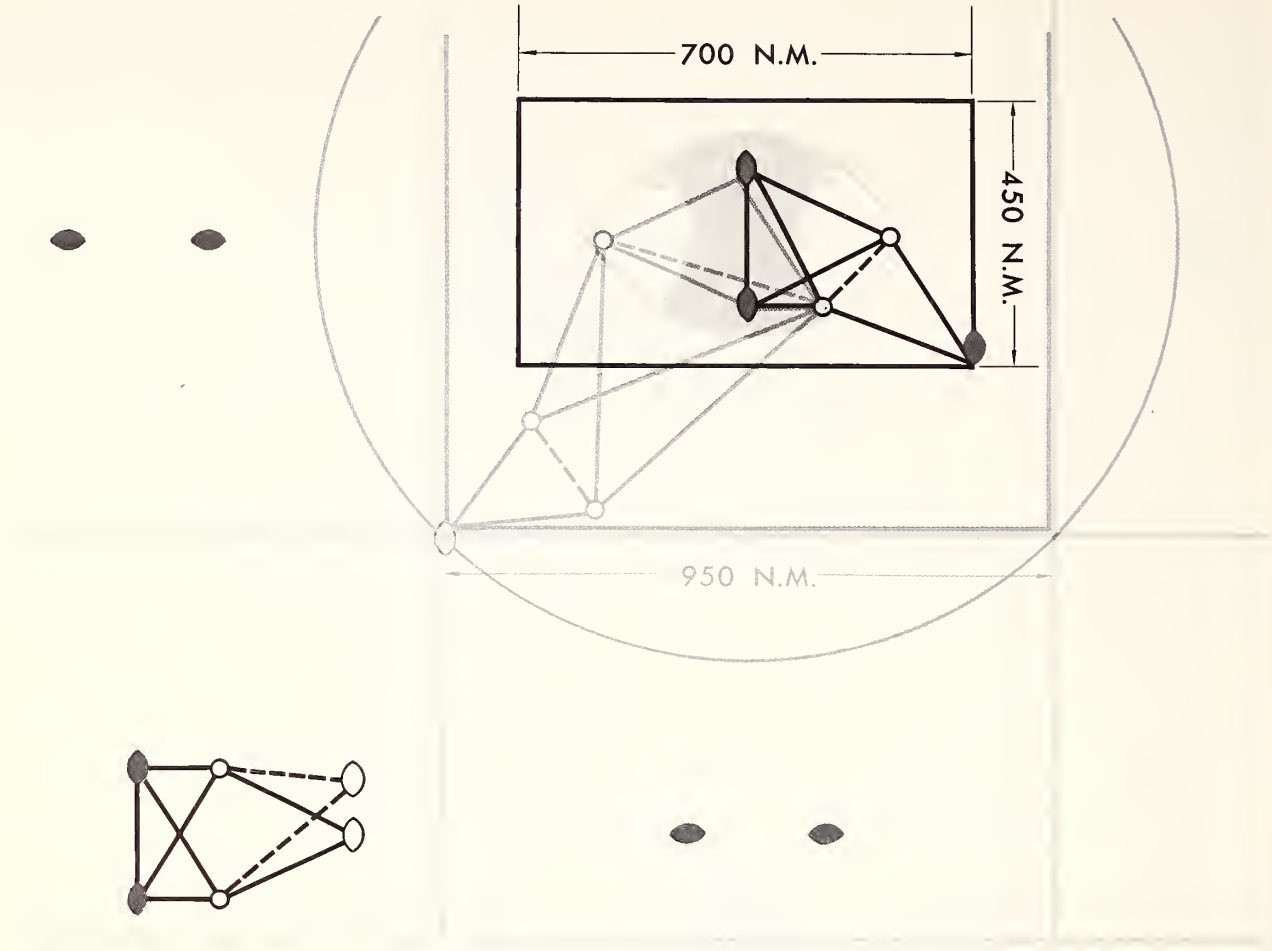

FIGURE 7.—Control unit—1 airborne station.

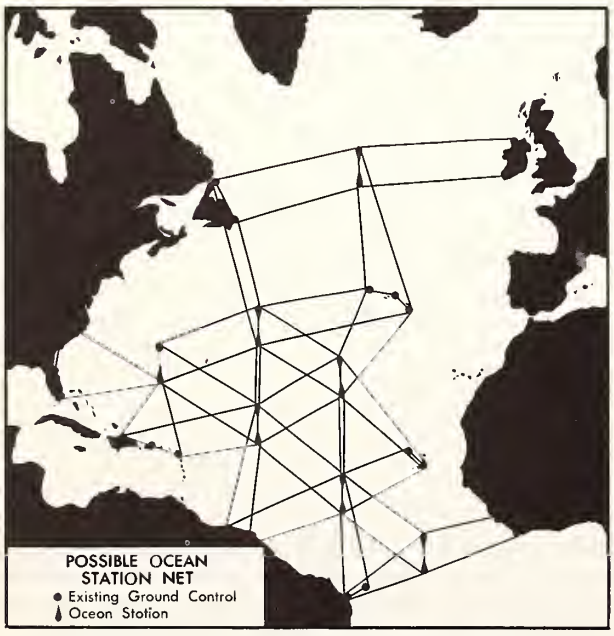

FIGURE 8.—Control extension spanning North Atlantic Ocean

however, has proposed building a version for drone operation in which the bulk of the equipment remains at the ground or ocean-surface station. It must be remembered that, in addition to the DME components, the air-station systems must include a precision narrow-beam radar altimeter for height measurement and a refractometer or the equivalent for determining index of refraction. These limitations are mentioned to point out that the drone idea was brought up only as a possibility, since the weight problem and problems of launch and recovery have not been fully explored.

The control extension and survey ship surveillance plan is presented only as a method offering some potential for solving marine geodetic problems. It is recognized that there are other methods to be considered and that some of these appear to be considerably less complex. It is urged, however, that the airborne DME concept be considered in any cost-effectiveness analysis conducted for the purpose of selecting a method for marine geodetic survey.

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Acoustic Navigation: Surface and Subsurface

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The ever-increasing need for precision in navigation, beyond the range of shore-based navigation aids and under the sea where navigation aids previously did not exist, has led to the development of a method of acoustic navigation. This system uses bottom-mounted acoustic transponders as fixed reference points in a manner comparable to the use of bench marks on land.

The transponders, arranged in a triangular array, receive interrogations from a ship and reply once to each interrogation. Shipboard equipment measures the elapsed time between the interrogation and the reply of each transponder, and this information is used to determine the ship's position relative to the array of transponders.

A major consideration in the design of an acoustic navigation system is the effect of temperature, salinity, and pressure on the velocity of propagation of sound through the ocean. These factors are not uniform throughout the body of ocean water, and the velocity of sound increases with increasing temperature, pressure, or salinity in sea water. For this reason a sound wave is refracted or bent as it passes through the medium.

Figure 1 is a plot of data taken in the Atlantic Ocean and illustrates how sound velocity varies with temperature and pressure from the surface to the bottom. Near the surface, for the first few hundred feet, the temperature is relatively constant and the velocity of propagation increases with depth as the pressure increases. Below that, the temperature falls steadily until, at a depth of about 4,000 feet, it has nearly reached its minimum value. In this region, the effect of the decreasing temperature upon the velocity of sound is greater than the effect of the increasing pressure, and causes a decrease in the velocity of sound. The velocity reaches a minimum at about 4,000 feet depth. Beyond that depth, the temperature remains relatively constant and sound velocity increases with increasing pressure until it reaches a maximum of approximately 5,050 feet per second at the bottom. The temperature at this depth is on the order of one or two degrees above zero centigrade.

This varying velocity of sound causes a sound wave traveling horizontally to refract or bend toward the layer of lower acoustic velocity. Thus from the bottom and in the very near surface layer, sound rays tend to bend upward. In the intermediate range, between approximately 200 and 4,000 feet, sound rays tend to bend downward. This effect produces a tendency for sounds generated in the minimum velocity area to be refracted back into this area, producing what is variously referred to as the sound channel axis or the Sofar channel.

The refraction of sound waves causes a surface coverage from a bottom-mounted transponder similar to that illustrated in figure 2. In the figure, sound waves projected horizontally from a bottom-mounted transponder are refracted upward as they travel outward. As the sound waves cross the sound channel axis, the increasing velocity gradient tends to refract the rays downward; very near the surface the rays are again bent upward.

Reflected from the surface, the waves go through the water to be either refracted or reflected from the bottom and again rise to the surface at a great distance from the point of initial contact.

This combined reflection and refraction of the sound rays produces shadow zones where the acoustic level of sound from the transponder is several orders of magnitude less than that found within the area of the surface grazing ray. Thus, practical acoustic navigation systems are limited in range by the depth of the water and the temperature conditions in which they operate. Practical surface ranges are defined by the zone in which the last direct ray reaches the surface; that is, by the outer limits of the first convergence zone.

Sound waves arriving at the surface at large horizontal ranges have travelled a curved path to reach a receiving hydrophone. This path is longer than would be represented by a straight line drawn between the projector and the receiving hydrophone. However, the actual sound path is in a higher velocity area for almost its entire length than is the straight line and the sound actually

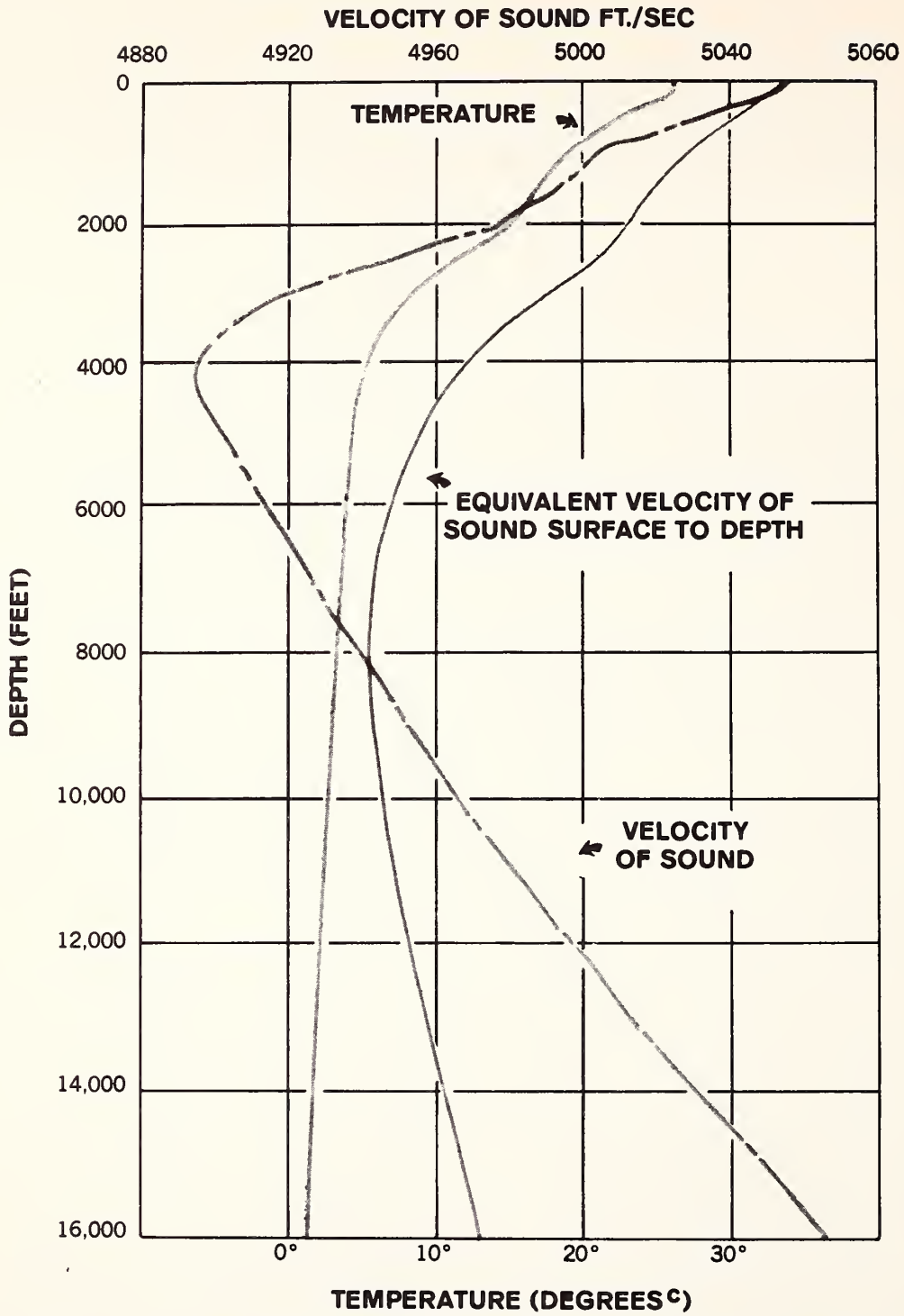

FIGURE 1.—Plot of sound velocity through sea water. Sample of data taken in North Atlantic Ocean, 25.05°N, 76.12°W, October 24-30, 1962.

arrives at the surface a bit sooner than would a sound wave theoretically following the straight line. If not compensated, this effect can produce an error in the slant range measurement of as much as 30 feet at a horizontal range of 15 miles.

A vehicle operating beneath the surface may extend the maximum range by a considerable distance when operating at moderate depth. When operating at very great depths, near the bottom, the maximum range of sound coverage may be much less than at the surface.

A factor which has been the subject of considerable discussion recently is the possibility of loss of signal due to cancellation as the vehicle

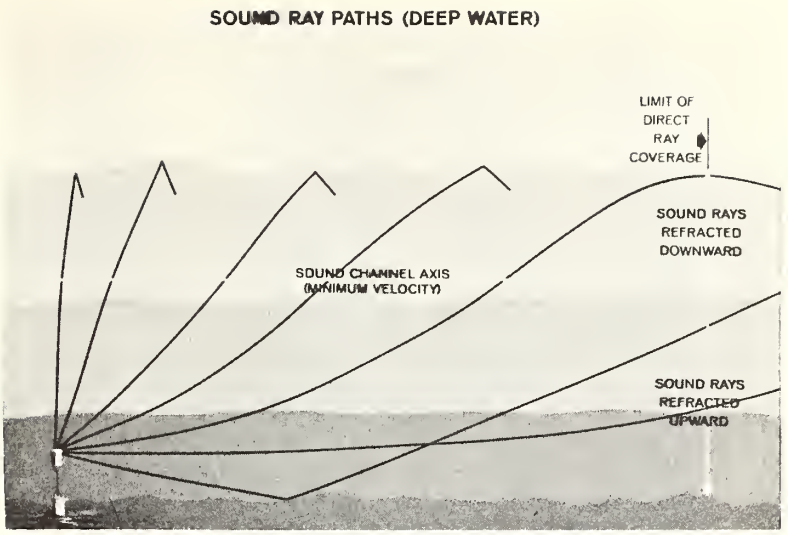
SOUND RAY PATHS (DEEP WATER)
LIMIT OF DIRECT RAY COVERAGE
SOUND RAYS REFRACTED DOWNWARD
SOUND CHANNEL AXIS (MINIMUM VELOCITY)
SOUND RAYS REFRACTED UPWARD

FIGURE 2.—Surface coverage of sound waves.

reaches a position where the direct ray path and the bottom-reflected ray path approach the same length. My experience indicates that only a moderate amount of bottom roughness would produce sufficient scattering of the reflected ray to prevent cancellation of the direct ray.

Additional range can be obtained both at the surface and near the bottom by raising the transducer above the floor of the ocean. Both surface conditions and bottom conditions may cause the maximum obtainable range to be less than illustrated. A surface layer which causes a sharp downward refraction of the surfacing ray or a bottom roughness which interferes with the horizontally projected ray from the transponder, both reduce the maximum obtainable range.

Raising the transducer above the bottom can introduce error into the position solution due to migration of the transducer caused by changing water currents. It is not always possible to provide sufficient buoyancy to hold transducer movement within tolerable limits.

Typical maximum horizontal ranges with the transducer 300 feet above the bottom in 3,000 fathoms of water would be on the order of 15 miles at the surface, 25 miles at moderate depth, and 4 to 5 miles near the bottom.

In shallow water, 1,000 feet or less, the refraction of sound waves may be as illustrated in figure 3. Under these conditions a vessel may receive many signals from a single transmission by the transponder. The signal from the direct ray path is the signal of interest and it is always

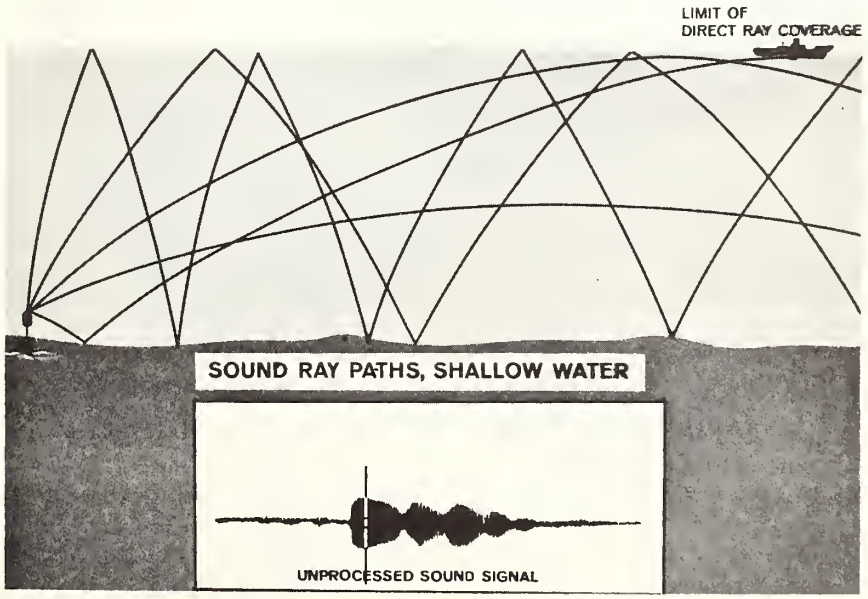

FIGURE 3.—Refraction of sound waves (1,000 feet or less).

the first to arrive, since it follows the shortest possible time path to the receiving hydrophone. The receiver need only be designed to respond to the first signal received and disregard those that follow.

The receiver in the transponder must respond to the first signal received and is then cut off for several hundred milliseconds to prevent multiple replies to a single interrogation.

In shallow water, accurate navigation of a surface vessel is limited to the area of direct ray coverage, but navigation at considerably reduced accuracy is possible over a much larger area. The shadow zones in shallow water are often not nearly as sharply defined as in deep water. A signal after a single reflection may still contain sufficient energy to operate the receiver.

A vehicle capable of deep operation can almost double the area of direct ray coverage seen by the surface vessel. It may, however, experience loss of direct ray signal even while operating quite near the transponder and near the bottom due to interference of bottom irregularities.

While the paths that sound rays follow in the water are independent of frequency, the attenuation experienced by each ray is not. Attenuation of sound waves in the ocean is caused by two independent factors: (1) spherical spreading loss; and (2) absorption loss.

Spherical spreading loss occurs as the sound waves travel outward to fill all space. This portion of the attenuation is independent of frequency and is expressed by an inverse square relationship.

Sound waves passing through water also suffer attenuation due to absorption. This effect at the frequencies of interest in acoustic navigation is approximately proportional to the three-halves power of the frequency.

The combination of the two effects produces the total attenuation with range and is a function of frequency.

Considering attenuation alone, it appears that the lower the frequency the longer will be the range for a given acoustic level and the better for acoustic navigation. However, the effects of the biological and physical background sea noise, and the size, weight, and cost of transducers must be considered.

Sea life many types of emit noises at all frequencies of interest which, in shallow water operation, become extremely important, but in deeper operations are relatively unimportant. An important source of background noise is the wave action and small bubbles containing air, collapsing as they hit the surface. This background noise source is strongly dependent upon the strength and duration of surface wind and is also frequency dependent. Since attenuation of noise is also proportional to frequency, the noise decreases with increasing frequency. Surface generated background noise also decreases with depth which is to the advantage of deep operating vehicles. Measurements of this noise resulted in curves originally published by Knudsen which show background noise plotted on a per cycle basis.

A practical navigation system is usually designed to operate at higher frequencies than dictated by purely attenuation and absorption considerations. Size and cost of transmitting transducers increases rapidly with decreasing frequency. The cost of providing the increased power is balanced against the cost of providing, supporting and stabilizing a larger transducer.

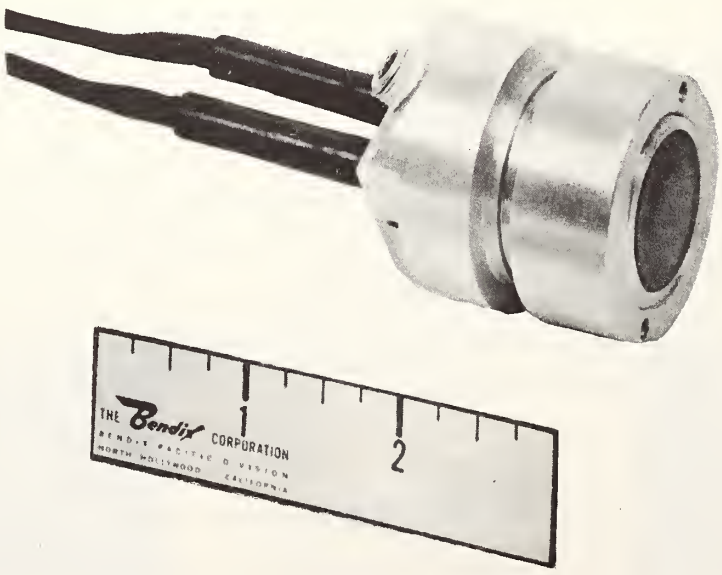

FIGURE 4.—Transducer, 40-kc operating frequency.

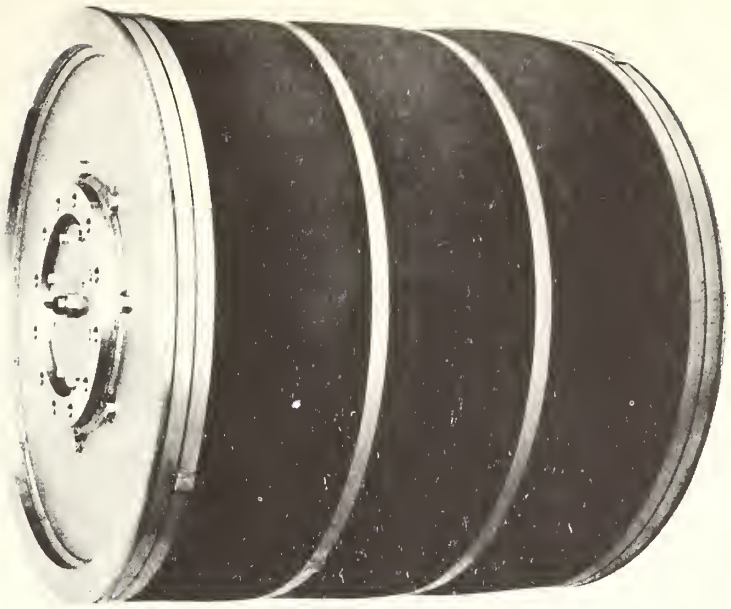

FIGURE 5.—Transducer, 1,500-cps operating frequency.

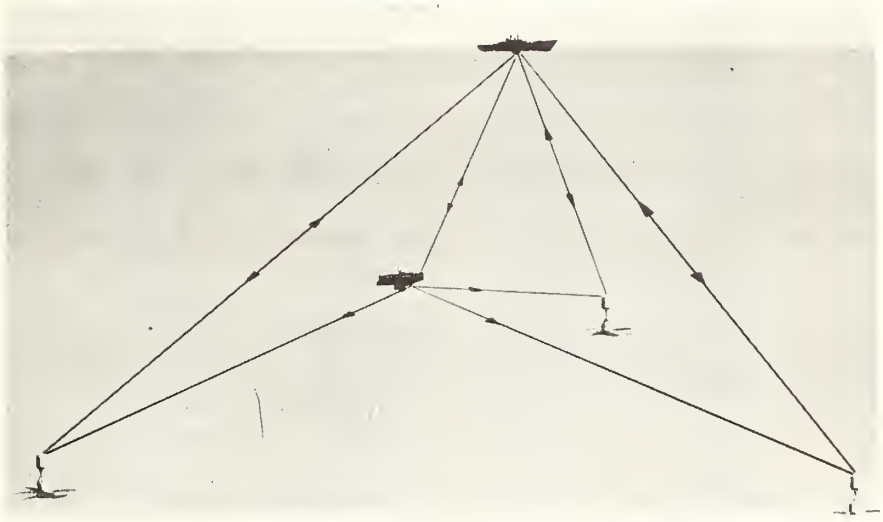

FIGURE 6.—Acoustic navigation problem.

To exaggerate this point to some extent, the transducer shown in figure 4 operates at 40 kc and the transducer in figure 5 operates at 1,500 cycles.

Figure 6 illustrates the acoustic navigation problem for both a surface vessel and a deep-operating subsurface vehicle. The spacing between transponders may be as short as one mile or as much as 9 or 10 miles, depending upon depth, accuracy requirement and type of operation.

In operation, the surface vessel transmits a single interrogation pulse of a few milliseconds duration and single frequency. The three bottom-mounted transponders receive the interrogation pulse and reply with a single pulse. Each transponder replies at a different preselected frequency. Equipment on board the surface vessel receives the replies from the transponders and determines the source of each reply by virtue of its frequency. By comparing the time of transmision of the interrogation pulse to the times of receipt of each reply, the slant range to each transponder can be determined.

If the spacing between the transponders and their depths are known, the slant range information can be used to determine the exact position of the ship relative to the transponder array.

The array dimensions are normally determined immediately after transponder installation. This is accomplished by conducting a velocity of sound propagation survey in the area and making slant range measurements while traveling a preplanned course through the array. A computer program which has been developed easily reduces the data to determine array dimensions.

A transponder is also located on the deep-operating subsurface craft. On alternate trans-

missions it is interrogated by a pulse of signal of a different frequency from that used to interrogate the bottom-mounted transponders. However, the reply frequency of the sub-mounted transponder is the same as the interrogation frequency of the bottom transponders.

From this reply the slant range from the ship to the sub is determined. This reply, being of the same frequency and pulse length as the interrogation signal for the bottom transponders, also initiates a reply from these transponders.

The ship is then in possession of all the information required to determine the three-dimensional position of the subsurface craft. The ship has the slant range to the sub, slant range to each transponder, and the sum of the slant ranges from the sub to the transponders plus the slant range from the ship to the transponders.

If the surface vessel is directing the operation, it may then transmit functional orders to the sub, If the subsurface vehicle is operating independently, position information may be transmitted to it from the surface ship.

If no communication link exists between the two craft, then the submarine must contain its own receiving, timing, and display equipment. It may then compute its own position with a small special purpose computer, or manually with the aid of nomograms.

The complete navigation equation for the position of the ship along the X axis of a coordinate system is shown in figure 7. Since most of the factors are constants, the equation may be simplified as shown in figure 8. The R's are slant range to the transponders and the K's are constants determined by the array dimensions.

The equation for Y and both of the equations for the position of the deep-operating vehicle reduce to a similar expression. The constant

$$X_S = \frac{R_A^2 (Y_C - Y_B)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)} +$$

$$\frac{R_B^2 (Y_A - Y_C)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)} +$$

$$\frac{R_C^2 (Y_B - Y_A)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)} -$$

$$\frac{(X_A^2 + Y_A^2 + Z_A^2)(Y_C - Y_B)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)} -$$

$$\frac{(X_B^2 + Y_B^2 + Z_B^2)(Y_A - Y_C)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)} -$$

$$\frac{(X_C^2 + Y_C^2 + Z_C^2)(Y_B - Y_A)}{2X_A (Y_B - Y_C) + 2X_B (Y_C - Y_A) + 2X_C (Y_A - Y_B)}$$

FIGURE 7.—Equation for X axis.

$$X_S = K_1 R_A^2 + K_2 R_B^2 + K_3 R_C^2 - K_4$$

$$Y_S = K_5 R_A^2 + K_6 R_B^2 + K_7 R_C^2 - K_8$$

$$K_1 = \frac{Y_C - Y_B}{2 [X_A (Y_B - Y_C) + X_B (Y_C - Y_A) + X_C (Y_A - Y_B)]}$$

FIGURE 8.—Simplified X-axis equation.

in the equations for the deep vehicle are more complex due to the third dimension.

The navigation accuracy possible with a circle drawn through the three transponders of an array is on the order of a few feet. However, the practical limitations in obtaining data such as the velocity of propagation of sound and array dimensions produces an accuracy of a few yards.

Transducer placement on the deep-operating vehicle must be given careful consideration. While operating at moderate depths, signals will be received from above and below. When near the bottom, signals will be received from above and horizontally, and if operating near a tall transponder, all signals will be from above the sub.

Probably the only solution is to place transducers on the top and the bottom of the vehicle in positions where they will least likely be in a structural shadow area.

Transducer radiation pattern is a careful compromise also. The ideal radiation pattern is very difficult to achieve in single element construction and arrays are expensive, heavy, and large.

A practical transponder will consist of five basic subassemblies: A power supply, a buoyant assembly, an electronic assembly, a transducer, and an anchor. In long-life transponders, it is convenient to combine some of these basic elements. The transponder in figure 9 combines the power supply and anchor and combines the electronic assembly and the transducer.

The power supply for the transponder consists of lead/acid batteries contained in a metal drum. The space inside each cell of the batteries above the electrolyte and the space between the battery cases is completely filled with transformer oil. An expansion bladder with an opening to the outside sea water is also contained in the metal housing. The batteries operate at the full hydrostatic pressure. The expansion bladder is used to compensate for internal volume changes due to temperature and the small amount of compression of the oil with pressure.

It is a curious fact that the bottom of the ocean is an ideal operating environment for lead/acid batteries. The low temperature keeps the internal self-discharge to a very low level. The high pressure limits gassing during discharge and provides an intimate contact between the electrolyte and the plates, increasing the capacity. For example, a 120-ampere-hour battery at room temperature and atmospheric pressure will pro-

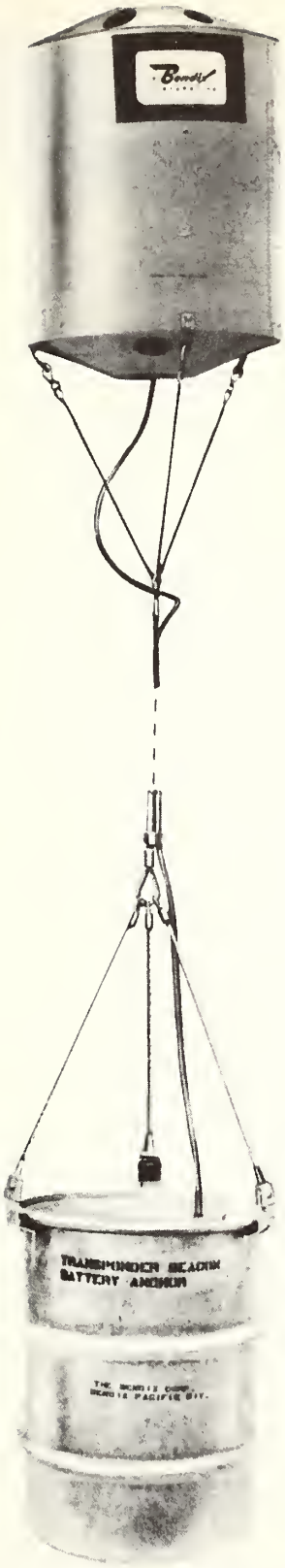

FIGURE 9.—Basic transponder assembly.

vide 160 to 180 ampere hours at the bottom of the ocean.

The design life of the battery supply is one year of shelf life plus one year of active life during which it will reply to 10^6 interrogations; about one every 32 seconds during the year. With normal usage these transponders have been operating at full power for over three years.

Due to the weight of lead/acid batteries, a separate anchor is not required. A net negative buoyancy of approximately 350 pounds is provided in the configuration shown.

The use of thermo-nuclear or isotopic power sources is being considered for transponders. However, their cost, when balanced against the cost of transponder replacement, has made their use economically impractical.

The buoyant assembly consists of 10-inch glass spheres imbedded in a free-flooding matting and contained in a fiber glass housing. The dry weight of the assembly is only about 100 pounds. The glass spheres are capable of withstanding in excess of 12,000 psi. The assembly provides about 100 pounds of buoyancy.

An earlier version of this transponder utilized a kerosene filled steel drum as the buoyant element which weighed over 900 pounds in air and provided only 90 pounds of buoyancy.

The transponder is designed for free-fall to the bottom and descends at a rate of about 5 feet per second. Its physical configuration and distribution of drag are such that it will fall straight down except for the effects of currents through which it passes. A shock mitigation pad on the bottom of the battery package prevents damage upon impact with the bottom.

The electronic assembly is mounted in the center of the buoyant unit and is shown in figure 10. It consists of a receiver, transmitter, and control circuits in an aluminum pressure housing. The transducer is designed to serve as one end-cap of the pressure housing.

Six different transmitting frequencies in this unit are selectable externally before launching.

The transducer is both hydrophone and projector, is oil filled, and operates at ambient pressure. It is a high-efficiency longitudinal vibrator using lead-zirconate-titanate ceramic as the active element. The transmitter and the receiver are both connected to the transducer at all times to eliminate the possibility of low-level switching noise. Receiver input protection is provided to prevent damage to the receiver during transmission.

A useful type of transponder is one designed for short life and recovery. The requirement for short-term navigational accuracy exists in search and rescue operations, bottom and sub-bottom mapping, oceanographic surveys and many other applications. Such a transponder is shown in figure 11.

The power source in this transponder is a pressure protected, recharging nickel/cadmium battery package. The useful life is 15 days.

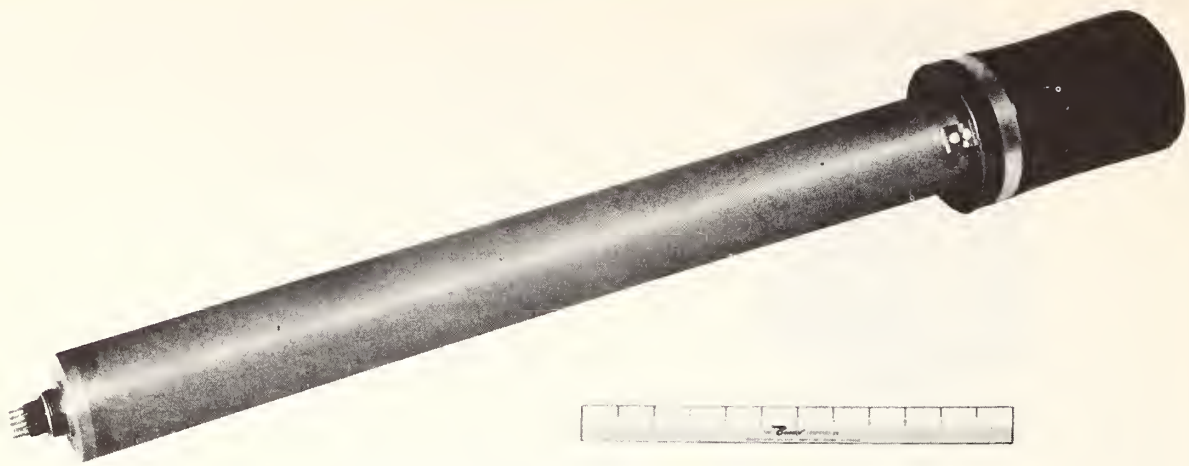

FIGURE 10.—Transponder electronic assembly.

At the bottom of the battery package is a release mechanism which can be actuated upon acoustic command from the ship or by an internal back-up timer. The transponder uses a disposable clump anchor of concrete, metal, or sand.

Since release occurs below the battery package, the transponder is operable while ascending to the surface. This feature permits the recovery vessel to be near the transponder when it surfaces. Auxiliary locating aids such as the flashing light at the top are useful in locating the transponder on the surface.

Another transponder design has the center of buoyancy and the center of gravity arranged such that the transponder turns upside down after reaching the surface. This keeps the transducer submerged while the transponder is floating on the surface, permitting interrogation as an aid to location.

One of the major problems associated with the use of transponders as a means of navigation, has been in the launch phase. Several transponders have been damaged in launching in heavy seas or from small vessels. The overall length of a transponder is on the order of 25 feet, requiring a relatively long boom to lift the battery pack or anchor clear of the deck and rail so that it can be lowered into the water and released. This problem is increased if steerage way must be maintained.

The solution to the launch problem is a transponder which has the battery package rigidly attached to the bottom of the buoyant section. The transponder is launched by simply rolling it over the side or stern of the vessel. In this configuration it may also be launched in complete privacy by firing it from a submarine torpedo tube.

The transponder falls to the bottom as a single unit and upon reaching the bottom, separates and erects itself into the conventional attitude.

In a recent system called ship-tended acoustic relay (STAR) where the transponder was required to perform control and acoustic telemetry as well as acoustic navigation functions, the electronic package became quite large. Due to the great depth at which it was required to operate, it became impractical, for weight reasons, to attempt to protect from pressure this large volume of circuits. It was decided to operate the entire circuit at the full ambient pressure.

Individual transistor cases were pierced and the internal volume filled with a high purity silicone jell to prevent contamination of the active element. Each transistor was then fitted with a pressure equalizing, silicone-filled cap. One of the transistors is shown in figure 12. Paper and oil-filled capacitors were pierced and completely filled with oil. Resistors, moulded capacitors, and other components were selected for their ability to operate without change at pressure with no modification.

The entire assembly was then placed in a relatively thin-walled container and completely flooded with oil. The container was fitted with a pressure equalization bellows which also compensates for volume variations due to temperature.

The pressure-equalized circuits perform in a perfectly normal manner with no unusual characteristics due to environment. An excellent heat sink is provided by the oil and sea water. This permits in some instances, the use of components with lower heat dissipation characteristics than could be tolerated in air. One of the electronic packages is shown in figure 13.

The obvious advantage of pressure-equalized circuits is in the great reduction in housing weight, particularly in large equipment. This can be of great importance in deep-operating vehicles.

The disadvantages are cost of certain components and service problems associated with the oil flooding.

FIGURE 11.—Short-life transponder assembly.

Since certain of the control and acoustic telemetry functions require continuous transmission, the power requirement is high. The battery package for the STAR transponder is shown in figure 14. This power supply operates at ambient pressure and provides continuous operation for over a year. Its dry weight is 10,000 pounds.

FIGURE 12.—Transistor used in deep-sea operation.

The shipboard equipment used in acoustic navigation is relatively conventional. Figure 15 shows a complete shipboard system except for a computer. The main equipment rack consists of transmitter, receiver, timing control, and readout equipment. Other equipment shown is the computer buffer with tape punch, shipboard transducer, precision graphic recorder, and a transponder test set for final transponder test and selection of transponder transmitting frequency and release code.

Slant range measurements are made on a set of counters. The counters are started upon interrogation of the transponders and allowed to run until replies are received. The outputs of the receiver channels are connected to the stop circuits of the counters. When a reply is received from a transponder, it is processed in the receiver channel tuned to that reply frequency, and a pulse is produced to stop the appropriate counter.

Depending upon the frequency that was being counted, the output of the counter will be the slant range to that transponder in yards, meters, feet, or time in milliseconds.

Since the receivers in the transponder and in the shipboard equipment require time for pulse recognition, or integration time, the count must be compensated to allow for this time. This is accomplished by delaying the start of the counters after the interrogation pulse by an amount of time equal to the sum of the two receiver recognition times.

Outputs from the shipboard equipment are range in visual readout, printed paper tape, punched

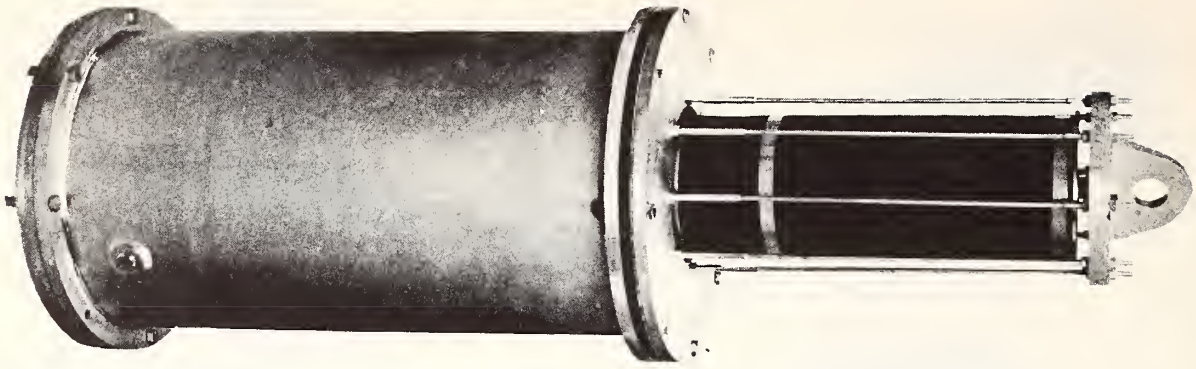

FIGURE 13.—Electronics package for deep-operating system.

paper tape, precision recording and computer format in straight binary or binary coded decimal as required.

Acoustic navigation places stringent requirements upon the receivers in the transponder and the shipboard equipment. Recognition of a single pulse must be positive and false recognition must be negligibly low. The shipboard receiver operates in a particularly noisy environment.

The receiver circuit that has been found to possess startling interference rejection consists of a low noise preamplifier followed by a wide band filter, a series of limiting amplifiers, and individual channel narrow band filters. The narrow band filters are followed by power detectors and integrators. The gain of the limiting amplifiers is sufficient to produce a hard-clipped output at zero sea state input level. The band width of each narrow band filter is approximately one-tenth that of the broadband filter.

Since the clipper amplifier output is in hard clipping at the input self noise level, the dynamic range of the tone filter outputs is limited to the ratio of the bandwidths or approximately 10 db. In essence, the signal and/or noise is forced to conform to the characteristics of the narrow band filter down to the -10 db points on the filter skirts.

Signals of a frequency outside the -10 db points on the narrow band filter, cannot produce a false output regardless of input level. The receiver is capable of rejecting 100 db of interference signal within the broad band with a tone filter possessing only 15 db of c-w rejection.

In a similar manner, in-band white noise cannot produce a false output regardless of level.

A coherent signal-to-noise ratio of 0 db in the broad band is sufficient to produce a 99 percent probability of detection.

The results that have been obtained through the use of acoustic navigation have been very satisfying. The many different requirements of the government have resulted in the development of a wide variety of low cost transponder types.

The use of acoustic navigation has been directly responsible for the relocation of certain small islands in the Atlantic which were shown on the charts as much as two miles out of place.

A network of acoustic transponders covering the entire Atlantic has been proposed. This would permit the updating of inertial and other navigation equipment at regular intervals.

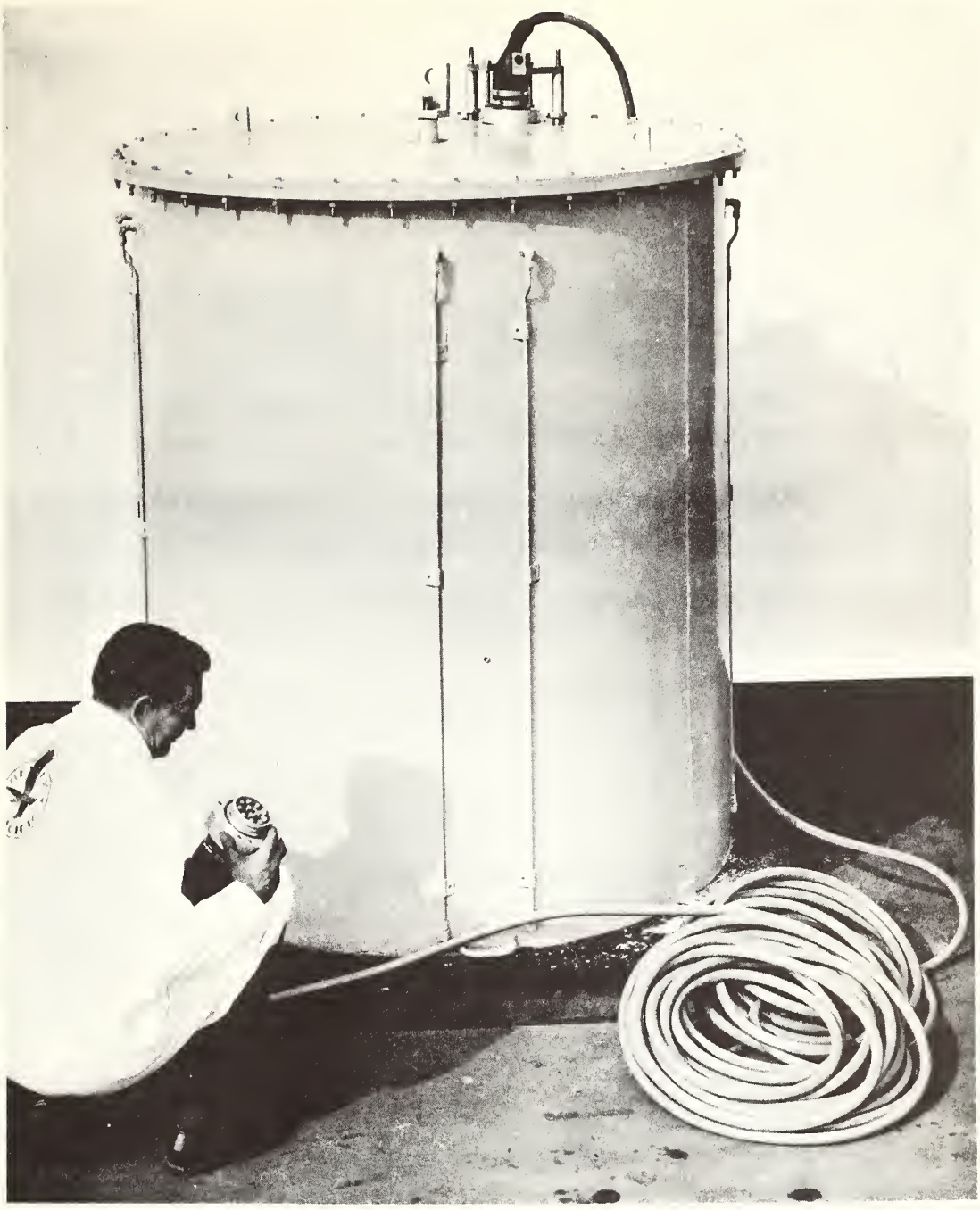

FIGURE 14.—STAR system battery package.

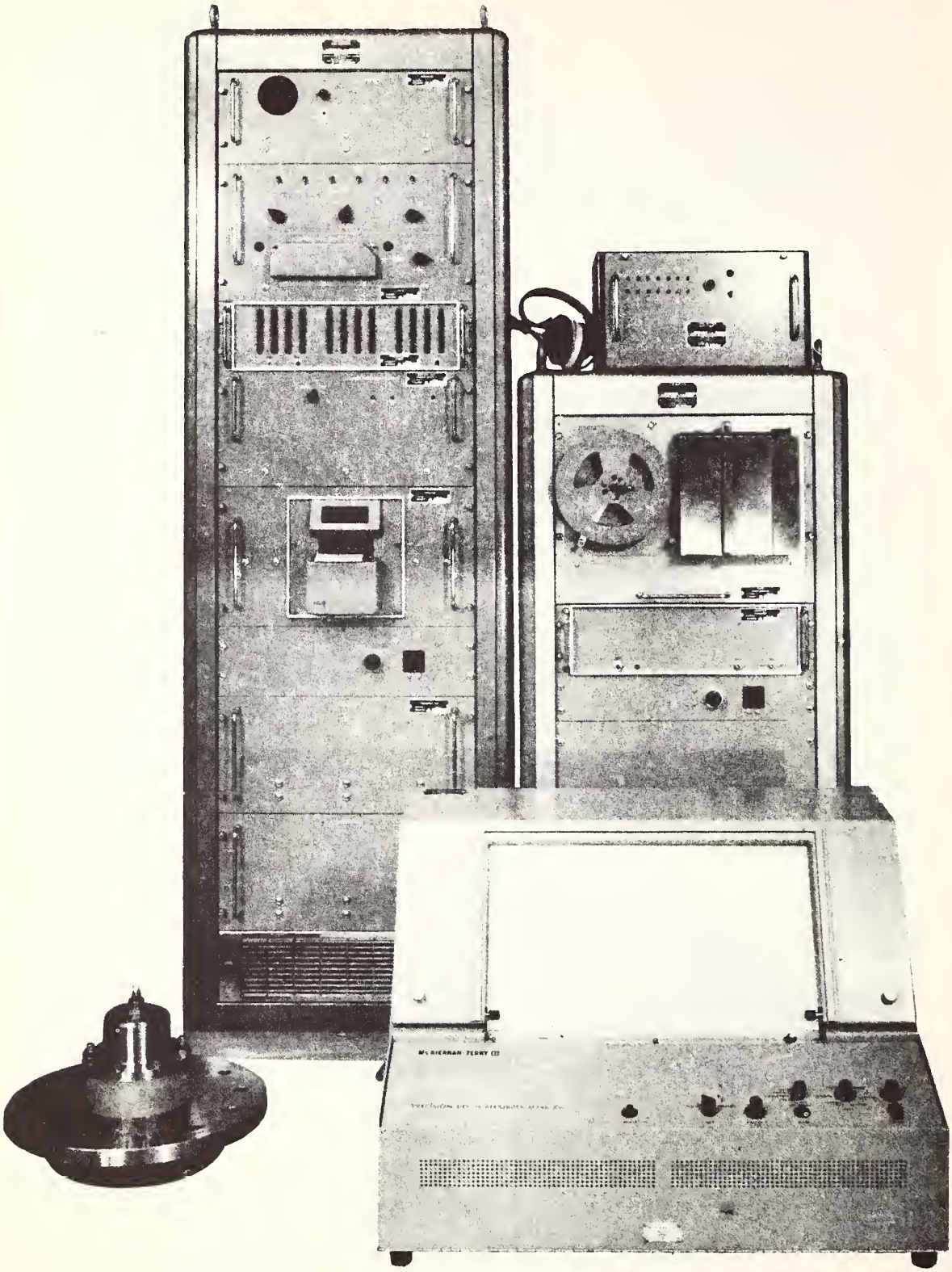

FIGURE 15.—Acoustic navigation shipboard system.

Session III Panel Discussion

A.G. BOGOSIAN, *Chairman* (Kollsman Instrument Corporation, Elmhurst, N.Y.).

MR. SNYDER (Naval Oceanographic Office): Mr. Ferrara would you please briefly describe your method for calibrating your electronic systems.

MR. FERRARA: Do you mean how we run our calibration system?

MR. SNYDER: Yes. Once you have a Raydist system manned, and you have a ship at sea, how do you know you are getting the ship's true position? Do you use theodolites on shore to check it?

MR. FERRARA: The Coast Survey usually does it by bringing the ship close to shore and taking three-point fixes, using sextant angles. I know of no other way. Normally, I do not have to worry about that problem.

MR. KOCHANSKI (Naval Applied Science Laboratory): I would like to ask Dr. Spiess about the accuracy of measurements obtained with the beacon system. You claim a 3-meter accuracy. What did you compare this against?

DR. SPIESS: This goes back to the question of what you determine the geometry to be in a transponder situation. We have three transponders down. If you make observations of the ranges of these transponders from 3 points you have, in principle, information to compute the geometry of the transponder layout. You can go beyond this and make observations at a large number of points so that you have a highly overdetermined system. Then, using a computer, take all the sets of ranges from every one of your observed points and adjust the transponder locations to minimize the range errors for all the points. Essentially, you (1) use the ranges to compute the location of the transponders, (2) compute the calculated positions of the corresponding sets of ranges, and (3) compare the differences between the calculated and observed ranges.

DR. TYRRELL: You have never actually measured the accuracy, for example, against Loran?

DR. SPIESS: This is an internal accuracy of the system. It has nothing to do with geodetic accuracy in terms of latitude and longitude.

DR. TYRRELL: No. What I mean is relative accuracy.

DR. SPIESS: What this means is that the mean square residual error that was left, after the transponders were put in the best possible places to insure compatibility, was 3 meters.

DR. OSTENSO (Office of Naval Research): I would like to ask Mr. Dean, is the Indiana site for the Loran transceiver proposed, or is it your personal idea?

MR. DEAN: It is proposed. My understanding is that funds have been allocated for it. The Coast Guard is going ahead with the program to set up the Indiana station.

Question from floor: Is there a projected date on this?

MR. DEAN: I do not know.

Question from floor: This is directed to Dr. Spiess on the transponder system. In regard to the towed body, you did not say anything about the depth of the tow or the speed at which you could operate, also whether the tow needs to be kept at a constant height above the bottom. If it does, how do you manage it?

DR. SPIESS: In describing the techniques, I concentrated primarily on the navigational situation. The towed body I was working with is capable of going down about 3,000 fathoms or so. In the tests mentioned, it was down 2,000 to 2,100 fathoms. The distance from the bottom depends upon the type of survey equipment. When doing narrow-beam echo sounder work and magnetometer work, we do not have to maintain a particular fixed distance above the bottom. If we are working with Sonar, for example, it is advantageous to maintain a reasonable constant distance off the bottom, typically of the order of 20 fathoms or so. The speed is of the order of 1.5 or 2.0 knots.

Question from floor: I have a question for Mr. Dean on the Omega system. He pointed out that the diurnal pattern allowed only 4 hours per day on that particular pair. I was wondering if you would comment on the amount of time that would be available, considering the fact that you can always hear at least 5 of the 8 stations?

MR. DEAN: I was not speaking about the availability of the signals, but rather that most of the time when you try to operate with, for example, 3 stations, there is a very short period during the day when all 3 of the stations are all in daylight or all in darkness. You are in what is regarded as a transition period most of the time. I admit I have not made a complete worldwide analysis of this, but this is the way most of the data appear to look.

DR. ORLIN (Coast and Geodetic Survey): This is for Mr. Lipsey or Mr. Ferrara. For either a long-range or short-range distance, assuming that

I do not care to know where I am but take positions at 10-, 20-, or 30-minute intervals, how accurately can I compute the distance between these 2 points?

MR. LIPSEY: This may depend on where you are. It may depend on what particular system you are able to receive. If you are able to use one of the precise surveying systems, then you can get the repeatability of that type of system. If you are where you can receive only the Omega system, then you are limited to the accuracy of that system, which may be of the order of 1,000-foot repeatability or accuracy from point to point without regard to knowing where you are.

DR. ORLIN: For a short period of time, is there a possibility that the 1,000 feet is more systematic than random?

MR. LIPSEY: The limitations with the Omega system are the instrumental accuracies. I would like to ask Mr. Palmer what the instrumental accuracy of a typical Omega receiver is going to be.

MR. PALMER: A typical Omega receiver is sensitive to 1 or 2 microseconds. There is a split here in the type of operation we are discussing. Wave length has much to do with the differential operation of Omega. Unfortunately, receivers have not been built which will adequately explore the amount of correlation over a few miles between the Omega system, because anything under 25 miles with the present receivers you are limited by the differences from receiver to receiver so that what the actual correlation is over short distances is not adequately known at this time.

DR. NETTLETON (Geophysical Associates): My question has been answered largely by the remarks, it concerns the practicality of using the Omega system for relatively near offshore work by using a shore monitor.

MR. LIPSEY: We discussed this yesterday and Mr. Palmer cited some statistics on the differential Omega that indicated that for distances to 25 miles the correlation is hidden in the instrumentation; for distances of 100 to 200 miles the correlation starts to disappear and the effectiveness of a shore monitor decreases rapidly; and for distances beyond 200 miles, the concept of Omega as a differential system disappears because of the difference in the propagation paths.

MR. BOGOSIAN: I would like to ask the Panel for comments. Dr. Browne is here from Cambridge, England, and has distinguished himself in many fields of geodesy. Dr. Browne, would you like to make any comment?

DR. BROWNE: One point has interested me very much and I thought perhaps Dr. Orlin's question would reach it. We have heard a lot today about the question of determining position. There are a few of us who are very much concerned with determining velocities. I am thinking of those people who measure gravity from ships or aircraft. The velocity, or, in particular, the Eötvös correction, is a thing you have to know, as was pointed out yesterday, to a precision of something like a 1/5 or 1/10 of a knot. This is what we would like very much to do. We have heard a great deal about position, but so far nothing about speed determination. I think it is a problem that worries everybody. We have tried from Cambridge (in England), in collaboration with the British Navy, several different sorts of experiments and we certainly do not have a good answer for deep water. We have succeeded in doing trials in shallow water where I think we were able to determine speeds to something like a few hundredths of a knot in a few minutes. I think that is a rather high accuracy. You see the trouble is that these gravity meters have response time of only 3 or 4 minutes, and they couldn't care less what the speed was 10 minutes ago. What they want to know is the average speed over the last 3 minutes, and you want to know that speed to 1/10 knot. This, insofar as I know, is a very, very difficult thing to do. We nearly obtained this speed accuracy under rather good conditions. Quite frankly, we found a really good answer by using an old-fashioned system, that was used at one time by the Coast and Geodetic Survey—simply throwing a sinker over the stern attached to piano wire. You let the piano wire run out over a wheel and you count the turns of the wheel. The wheel turns around for every thousandth of a mile you move along. You sit there with a stopwatch and count, or until you get tired and use an automatic recorder which you kick each time the wheel goes around. From this you are able to get—providing the sea is fairly shallow and of a fairly steady depth, and providing the taut wire is not broken—the speed accuracy you need. Even though this is an application of a very old-fashioned method, it is still the best one to use.

MR. BOGOSIAN: Mr. Alvey, do you have any remarks you want to give us at this time?

MR. ALVEY: I have a question I wish to address to Dr. Tyrrell. In the last slide that you presented, showing the accuracy figures, you indicated that practically with a Sonar transponder system, I presume you can get somewhere between 100 and 50 feet. Was this for 1 transponder or were you referring to a system of a multiple number of transponders on the bottom?

DR. TYRRELL: This was conceptually with regard to a field of transponders, or at least a triangle, but I did not completely cover it in this talk. However, I think you will see by looking at the rather hypothetical figures I quoted versus those actually realized, it is a different situation, but what I quoted as a possible ultimate accuracy

of 10 feet was meant to be not that achievable under some rare fortuitous circumstances, but the day-to-day accuracy throughout an area, let us say for each triangle, perhaps 10 by 10 miles, and also the accuracy easily realizable without a tremendous screening of large quantities of redundant data. I think the acoustic systems can give this type of internal consistency of the network.

MR. WILLIAMS: I wish to congratulate Colonel Robson for his boldness in offering a new concept of flying a box-measuring formation but I would recommend that you include a fire ax with your proposal to cut through all the closed doors.

COL. ROBSON: I really am not quite as bold as Mr. Williams suggests. This appears to be a rather radically new attempt. For some past months this very same scheme of using airborne pickets to patrol the positions of other low flying aircraft has been in use by one of the Task Forces. It is not as new as it might appear.

MR. SALTZER (North Pasadena): During coffee break, Dr. Tyrrell mentioned a method of ranging that should show much promise, for new systems may use built-in clocks rather than transponders. We now have the capability of building fairly accurate clocks. Would anyone else care to comment on the possibility of using clocks rather than transponders?

DR. SPIESS: If you examine the full text of my paper, you will find a statement that in the long run a system using pingers that ping at a predetermined time may be the system that will be most useful in the future, particularly when you have several users in an area. Transponders can be rather messy if you have several different people interrogating transponders at one time. We have had as many as 3 different gadgets all interrogating the same transponder. By the time we have everything sorted out, we feel that we have done a day's work. If these 3 or 4 vehicles were, in fact, completely independent, they would have to rely on some sort of a communication link to tell each other what they were doing. It would be much better to put down markers that would ping at specific times. I think the requirements for clocks would be a system that had a drift of a millisecond per day. That is not asking too much for clocks these days, although it may be asking quite a bit for a clock that is to be thrown away.

MR. BYRD (NASA): I have a question for Dr. Spiess. How do you relate the position of the towed fish to the ship?

DR. SPIESS: In the first place, all of our survey equipment is down in the towed fish. The position of the fish is determined relative to transponders. For a fair amount of our survey work, we have been able to navigate both the fish and the ship relative to the same set of transponders. This facilitates the ship-handling problem when you are trying to determine what effect the motion of the ship has on the motion of the fish. Does that answer your question?

MR. BYRD: I was wondering if the ship's position was important to you.

DR. SPIESS: In some instances, yes. If we try to track it relative to the same set of transponders.

MR. BOGOSIAN: Thank you. Session is adjourned.

Absolute Position Determination of Sonar Beacons

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ABSTRACT

A technique is described in which bottom-moored sonar beacons are surveyed in absolute (geodetic) position coordinates. The shipboard equipment consists of a sonar transmitter/receiver and a celestially augmented inertial navigator. Errors in the survey are shown to depend upon errors in the sonar measurements along with the celestial observation error and inertial navigator dynamical errors. Maneuvers are described and navigator reset techniques are discussed which serve to minimize the overall survey error. The effect of repeated measurements is analyzed to indicate the role it plays in error reduction.

I. INTRODUCTION

During the last decade, precise navigation in limited areas of the world's oceans has become a matter of increasing importance. One factor that has been of great significance in motivating this interest has been man's ventures in space and the consequent need for precise tracking. For many space missions, the coverage provided by land-based tracking stations does not suffice. Ships at sea may then be utilized in their stead. While the location of the sensors at a land-based site must be surveyed to determine their geographical coordinates precisely, techniques exist which allow this to be done with relative ease. The shipboard sensor is, however, on a base which is in motion relative to the earth. Thus, its location is, at once, a dynamic quantity which is difficult to measure.

The foregoing provides only one area in which requirements exist for precise determination of absolute position at sea. Other requirements exist in the areas of oceanology, offshore oil recovery, offshore mining and fishing, as well as deep-sea search, location, recovery, and salvage operations.

There are, of course, a variety of ways in which the problem may be solved. One involves the use of radio navigation aids such as Loran and Lorac. These systems are generally not accurate enough for the successful fulfillment of some of our anticipated space missions. They also suffer in that coverage is presently limited to specific geographical areas. The latter limits the use of these systems so that oil recovery, mining, etc. could only be accomplished in the areas provided with coverage. It also places constraints on the design of tracking networks for the space missions. Celestial navigation systems could be used but are only as dependable as the weather. Furthermore, while celestial navigation systems exist whose characteristics are adequate, large random errors (which average out over a period of time) may make individual position fixes poor.[1] Inertial navigation systems exhibit relatively accurate short-term characteristics but provide errors that grow with time.

A solution to the problem which allows the reduction or averaging of the random measurement errors before the actual use of the equipment involves the deployment of a set of bottom-moored sonar beacons. These may then be utilized as a local coordinate frame within which navigation can be performed. By skillfully using the accurate short-term properties of an inertial navigator and the inherent reduction in random error that results from smoothing repeated celestial observations, the beacons can be accurately surveyed. Although the errors in the survey can be no better than the systematic errors that exist in the shipboard navigator, the repeated measurements allow a significant reduction in random measurement errors. Of particular importance is the fact that the survey is carried out prior to the use of the beacons as a coordinate frame for navigation so that the error reduction occurs then, and is limited only by the amount of time spent

[1] Throughout this paper the celestial reference can be replaced by a navigation satellite (for example). The major qualitative differences are that the latter provides an all-weather capability without, however, heading information.

surveying and by the systematic errors in the navigator.

II. BEACON SURVEY

The process of surveying a beacon net involves the deployment of the required number of beacons in a prescribed pattern on the ocean bottom and the measurement of the absolute position of each beacon. The central issue of this paper is taken to be the latter, i.e., the technique of determining beacon position. Considerations pertaining to the number of beacons and their associated geometry are more closely related to applications and, hence, are not treated here.

The selection of an efficient survey technique is based primarily on the ability to accurately measure beacon position as rapidly as possible. Underlying this consideration are the effects of two sets of closely interrelated constraints, constraints imposed by the external environment and those imposed by the measurement equipment. Operationally, the survey is carried out by a ship at sea. The time to complete a survey is governed by such considerations as the required ship maneuvers (involving the associated execution times) and ship stability as a function of sea state. The limitation imposed by the measurement equipment alone is fundamentally one of accuracy and, time notwithstanding, is indicative of the degree of precision to which beacon position can be ascertained.

The measurement equipment falls into two categories: Onboard sonar equipment to carry out the necessary echo ranging, and navigation equipment for the instantaneous measurement of ship's position during the survey. The availability of a computer is implied.

The known methods of beacon location by echo ranging may be broadly classified in two distinct categories:

(a) Trilateration, that is, methods whereby the actual slant range to the beacon is measured from two locations of the ship, thus providing two legs of a triangle. The third leg, representing the displacement of the ship in going from the site of the first measurement to that of the second, allows the coordinates of the beacon to be computed.

(b) Methods in which the computation of beacon position is not explicitly dependent on slant-range. The Point-of-Closest Approach) technique of beacon surveying is one such member of this category. According to this technique, it is required that the ship successively travel along two constant heading tracks past the beacon. On each track the beacon is interrogated repetitively by the shipboard sonar and the respective points where slant range to the beacon is minimum (that is, the points of closest approach) are recorded. The coordinates of the beacon are obtained by observing that it must lie on the normal (plane) to a heading track through the points of minimum slant range. The intersection of the two normals then provides the horizontal coordinates of beacon position.

The latter technique has been selected for analysis in this paper. The choice has been based primarily on its simplicity. As is shown in Section III, the error in this method of surveying the beacon depends upon the heading error of the ship during the two constant heading tracks and the error in determining the instant of time, hence, the position of the ship, when minimum slant range is measured. Navigation errors, errors in determining the position of the ship at the time of the crucial measurement, also appear. However, navigation errors also degrade the accuracy of the trilateration method and, therefore, do not serve as a useful basis for comparison.

The complexity of trilateration is briefly shown by reference to figure 1. Measurements of slant

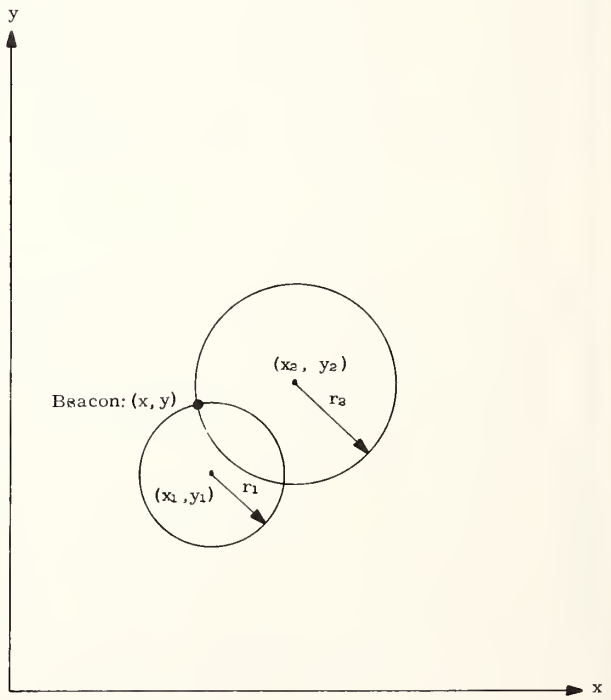

FIGURE 1.—Trilateration method of beacon surveying.

range to the beacon are made by the ship at two arbitrary points (x_1, y_1, and x_2, y_2). The equations that result are:

$$(x-x_i)^2 + (y-y_i)^2 = r_i^2 = s_i^2 - z^2 \qquad (1)$$

where s_i and r_i are the values of slant range and horizontal range to the beacon when the ship is located at (x_i, y_i) and z is the depth of the beacon.

The two relationships ($i = 1$ and $i = 2$) of the form shown in Eq. (1) are used to determine the position of the beacon (x, y) in the coordinate frame chosen. By allowing each of the terms in Eq. (1) to be an error by a small amount (such that second order error terms are negligible), the following error relationship obtains:

$$(x - x_i)(\delta x - \delta x_i) + (y - y_i)(\delta y - \delta y_i) = s_i \delta s_i - z \delta z \tag{2}$$

where $(\delta x, \delta y)$ are the components of beacon position error, $(\delta x_i, \delta y_i)$ are the ship's navigation errors, δs_i is the slant range measurement error, and δz is the error in the knowledge of beacon depth.

It is clear from Eq. (2) that errors in the computed position of the beacon depend not only upon depth and slant range measurement errors but upon the actual value of these quantities as well as the values of x_i and y_i. Thus, the results of the computation are sensitive to the geometry. This geometric error magnification has been described by Groginsky [1959]. While its effect on the beacon survey error may be minimized and perhaps not seriously degrade the final result, it does produce an added complication that does not encumber the Point-of-Closest Approach technique.

III. THE POINT-OF-CLOSEST-APPROACH TECHNIQUE

Since the region of required ship maneuvering for the measurement of beacon position is relatively small, the analysis to follow will be carried out on the basis of a "flat earth" approximation. Hence, referring to figure 2, it can be shown that the beacon coordinates, referenced to the local coordinate system,[2] are given by

where (x_1, y_1) and (x_2, y_2) are the points of closest approach along tracks (1) and (2), respectively, and θ_1 and θ_2 are taken as the track headings. It is the function of the navigation equipment to provide measures of (x_1, y_1, θ_1) and (x_2, y_2, θ_2).

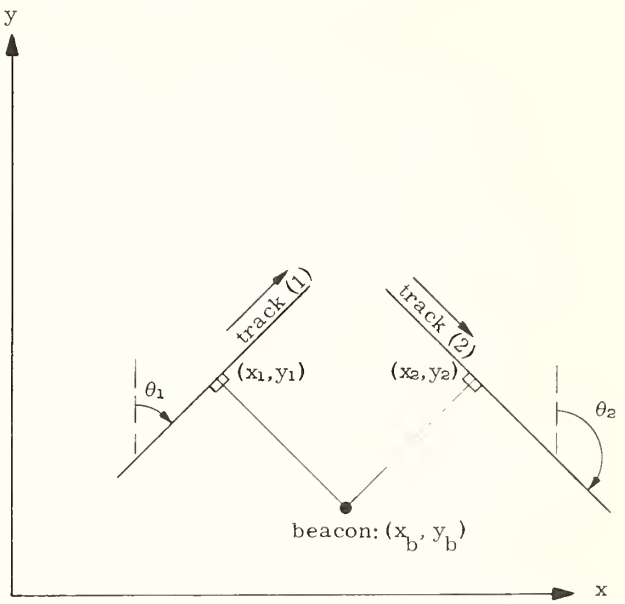

FIGURE 2.—Geometry of beacon position determination.

$$x_b = \frac{\frac{1}{2}(x_2 - x_1)\sin(\theta_1 + \theta_2) + \frac{1}{2}(x_2 + x_1)\sin(\theta_2 - \theta_1) + \frac{1}{2}(y_2 - y_1)\left[\cos(\theta_2 - \theta_1) + \cos(\theta_1 + \theta_2)\right]}{\sin(\theta_2 - \theta_1)} \tag{3}$$

$$y_b = \frac{\frac{1}{2}(y_1 - y_2)\sin(\theta_1 + \theta_2) + \frac{1}{2}(y_1 + y_2)\sin(\theta_2 - \theta_1) + \frac{1}{2}(x_1 - x_2)\left[\cos(\theta_1 + \theta_2) - \cos(\theta_2 - \theta_1)\right]}{\sin(\theta_2 - \theta_1)} \tag{4}$$

[2]The indicated x-y coordinate system is easily referenced to a geographic coordinate frame, that is, θ_1 and θ_2 are, effectively, heading angles.

The quality of a single estimate of beacon position is seen to be a function of the uncertainty in the position of minimum slant range along each track and the errors in the track heading indications. Assuming negligible second-order effects, the total errors in the components of beacon position are:

$$\delta x_b = \sum_{i=1}^{2} \left(\frac{\partial x_b}{\partial x_i} \delta x_i + \frac{\partial x_b}{\partial y_i} \delta y_i + \frac{\partial x_b}{\partial \theta_i} \delta \theta_i \right) \quad (5)$$

$$\delta y_b = \sum_{i=1}^{2} \left(\frac{\partial y_b}{\partial x_i} \delta x_i + \frac{\partial y_b}{\partial y_i} \delta y_i + \frac{\partial y_b}{\partial \theta_i} \delta \theta_i \right) \quad (6)$$

where the various partial derivatives are the sensitivities of the beacon coordinates to small errors δx_i, δy_i, and $\delta \theta_i$ $(i = 1, 2,)$ respectively.

If it is further assumed that all system errors are random in nature, the mean-square error (MSE) in beacon position, defined as

$$\overline{\delta P_b^2} = \overline{\delta x_b^2} + \overline{\delta y_b^2}, \quad (7)$$

is given by

$$\overline{\delta P_b^2} = \sum_{i,j=1}^{2} \left[\left(\frac{\partial x_b}{\partial x_i} \frac{\partial x_b}{\partial x_j} + \frac{\partial y_b}{\partial x_i} \frac{\partial y_b}{\partial x_j} \right) \overline{\delta x_i \delta x_j} + \left(\frac{\partial x_b}{\partial y_i} \frac{\partial x_b}{\partial y_j} + \frac{\partial y_b}{\partial y_i} \frac{\partial y_b}{\partial y_j} \right) \overline{\delta y_i \delta y_j} \right.$$
$$+ \left(\frac{\partial x_b}{\partial x_i} \frac{\partial x_b}{\partial y_j} + \frac{\partial y_b}{\partial x_i} \frac{\partial y_b}{\partial y_j} \right) \overline{\delta x_i \delta y_i} + \left(\frac{\partial x_b}{\partial x_i} \frac{\partial x_b}{\partial \theta_j} + \frac{\partial y_b}{\partial x_i} \frac{\partial y_b}{\partial \theta_j} \right) \overline{\delta x_i \delta \theta_j}$$
$$\left. + \left(\frac{\partial x_b}{\partial y_i} \frac{\partial x_b}{\partial \theta_j} + \frac{\partial y_b}{\partial y_i} \frac{\partial y_b}{\partial \theta_j} \right) \overline{\delta y_i \delta \theta_j} + \left(\frac{\partial x_b}{\partial \theta_i} \frac{\partial x_b}{\partial \theta_j} + \frac{\partial y_b}{\partial \theta_i} \frac{\partial y_b}{\partial \theta_j} \right) \overline{\delta \theta_i \delta \theta_j} \right] \quad (8)$$

where the bar notation denotes an ensemble average.

The operations indicated in Eq. (8) are, algebraically, quite formidable. However, there are two reasonable conditions which, when imposed, provide a considerable reduction in complexity. First, it is evident that the MSE in beacon position is dependent upon the relative orientation $(\theta_2 - \theta_1)$ of the two successively traversed constant-heading tracks. From a direct substitution of Eqs. (3) and (4) into Eqs. (5) and (6), it can easily be shown that a "best" choice for $\theta_2 - \theta_1$ is 90°, that is, the two heading tracks taken past the beacon should be orthogonal. Second, it is noted that the particular value of heading of the first track by the beacon is of little importance—any value will suffice. This implies that the expression derived for δP^2_b can be statistically averaged over θ_1 to yield an expression independent of heading [that is, θ_1 assumed to be uniformly distributed over $(0, 2\pi)$].

Invoking these two conditions, the following expression for δP^2_b obtains:[3]

$$\overline{\delta P_b^2} = \frac{1}{2} \left[\left(\overline{\delta x_1^2} + \overline{\delta y_1^2} + \overline{\delta x_2^2} + \overline{\delta y_2^2} \right) + R_{12}^2 \left(\overline{\delta \theta_1^2} + \overline{\delta \theta_2^2} \right) \right.$$
$$\left. + (x_2 - x_1) \left(\overline{\delta y_1 \delta \theta_1} - \overline{\delta y_2 \delta \theta_2} \right) - (y_2 - y_1) \left(\overline{\delta x_1 \delta \theta_1} - \overline{\delta x_2 \delta \theta_2} \right) \right] \quad (9)$$

[3] It is noted that the orthogonality condition ($\theta_2 = \theta_1 + 90°$) does not necessarily imply any analogous relationship between $\delta\theta_1$ and $\delta\theta_2$ for random errors. In computing δP^2_b, all correlation terms involving $\delta\theta_1$ and $\delta\theta_2$ must be interpreted in light of the fact that track (2) is initiated *after* track (1) is completed, e. g., if the error in the indication of heading possesses a nonstationary mode, then $\overline{\delta\theta_2^2} > \overline{\delta\theta_1^2}$.

where R_{12} is the distance between the points of minimum slant range:

$$R_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{10}$$

Now, with respect to Eq. (9), it is noted that the term $(\overline{\delta x_1^2} + \overline{\delta y_1^2})$ is the MSE in the position of the ship at the point where minimum slant range occurs along track (1). This error is, in turn, the sum of two contributing independent errors:

(1) The error (arising from noise in the sonar echo ranging) in determining the minimum slant range among those measured and, hence, the point along the track at which this occurs, and
(2) the navigation error in specifying the coordinates of this point.

Defining $\delta\eta_i$ as the error in determining the point of minimum slant range along track (i) and δx_{ni}, δy_{ni} as the concomitant navigation errors, reference to figure 2 indicates that

$$\delta x_1 = \delta\eta_1 \sin\theta_1 + \delta x_{n1} \tag{11a}$$

$$\delta y_1 = \delta\eta_1 \cos\theta_1 + \delta y_{n1} \tag{11b}$$

$$\delta x_2 = -\delta\eta_2 \cos\theta_1 + \delta x_{n2} \tag{11c}$$

$$\delta y_2 \doteq \delta\eta_2 \sin\theta_1 + \delta y_{n2} \tag{11d}$$

where the heading orthogonality condition has been used. Taking mean-square values of Eqs. (11a) - (11d), averaging over θ_1, and substituting into Eq. (9), there results

$$\overline{\delta P_b^2} = \frac{1}{2}\Big[\overline{\delta\eta_1^2} + \overline{\delta\eta_2^2} + \overline{\delta P_{n1}^2} + \overline{\delta P_{n2}^2} + R_{12}^2\,(\overline{\delta\theta_1^2} + \overline{\delta\theta_2^2}) + (x_2 - x_1)(\overline{\delta y_1\,\delta\theta_1} - \overline{\delta y_2\,\delta\theta_2}) - (y_2 - y_1)(\overline{\delta x_1\,\delta\theta_1} - \overline{\delta x_2\,\delta\theta_2})\Big] \tag{12}$$

where $\overline{\delta\eta_i^2}$ is the MSE in determining the *point* at which minimum slant range occurs along track (i) and $\overline{\delta P_{ni}^2}$ is the MSE in determining the *position* of that point.

(a) Determination of the Point of Minimum Slant Range

The point of minimum slant range is determined by a periodic interrogation of the beacon while the ship is steaming by on a constant-heading track. After the track is completed, the various values of slant range are calculated. *It is observed that the ship was closest to the beacon when the interrogation corresponding to the minimum value of slant range was made.* The error in determining the point at which the minimum occurs arises primarily from sonar receiver noise. Of particular significance is the fact that any transmission errors which tend to shift the slant range vs. position-on-track curve up or down[4] are of no consequence: *it is only the position of the ship at the time of occurrence of minimum slant range that is required, not the value of minimum slant range.*

The MSE in determining the point at which minimum slant range occurs is derived in the appendix. It is shown that

$$\overline{\delta\eta^2} = \frac{36\,K^2}{n^2\,(n^2 - 1)^2\,d^2} \sum_{i=1}^{n} s_i^2\,(n + 1 - 2i)^2 \tag{13}$$

where K^2 is the mean-square value of the range measurement error due to the sonar receiver noise (assumed stationary and uncorrelated), n is the total number of beacon interrogations, s_i is the slant range to the beacon at the time of the i^{th} interrogation, and d is the distance between beacon interrogations.

If it is assumed that the "interrogation density" and total number of interrogations are constant

[4]Included in this class are refractive errors and equipment biases.

from track to track, the MSE in beacon position, as given by Eq. (9), can now be written as

$$\overline{\delta P_b^2} = \frac{1}{2}\left[\frac{36\,K^2}{n^2\,(n^2-1)^2 d^2}\sum_{i=1}^{n}(s_{1i}^2 + s_{2_i}^2)(n+1-2i)^2 + \overline{\delta P_{n1}^2} + \overline{\delta P_{n2}^2} + R_{12}^2\,(\overline{\delta\theta_1^2} + \overline{\delta\theta_2^2}) + (x_2 - x_1)(\overline{\delta y_1\,\delta\theta_1} - \overline{\delta y_2\,\delta\theta_2}) - (y_2 - y_i)(\overline{\delta x_1\,\delta\theta_1} - \overline{\delta x_2\,\delta\theta_2})\right] \tag{14}$$

where s_{1i} is the slant range to the beacon at the time of the i^{th} interrogation along track (1) and s_{2i} is the slant range to the beacon at the time of the i^{th} interrogation along track (2).[5]

(b) The Error in the Position of the Point of Closest Approach

Although several possibilities exist for providing the required navigation information (such as, hyperbolic radio systems, navigation satellites, celestial trackers), the continuous availability of inertial information, in all sorts of weather and at any location on earth has prompted consideration of an augmented inertial navigation system for this function.

Errors contributed by an inertial navigator can be broadly classed in two categories—the Schuler loop errors and the earth loop errors [Gelb, 1965]. Both arise from undesired coupling of the platform instrumentation with the field forces of the earth. Schuler loop errors are due to the coupling between the platform accelerometers and the earth's gravity field. Earth loop errors are the result of the coupling between the reference gyros and the earth's spin vector. The precise form that these errors assume depends on the configuration of the navigator, the quality of the inertial instruments, and the magnitude of initialization errors and gravity computation errors.

Damping of the Schuler oscillation is ordinarily accomplished by the introduction of an externally derived velocity signal [Gelb, 1965; Porter and Kazda, 1961]. The effect of this is to alter the characteristics of the Schuler loop to that of a damped system. Of prime importance to the case of maritime navigation is the fact that the velocity information is usually provided by means of an electromagnetic log, an instrument which measures *fore-aft speed of the ship relative to the water*. Thus, water currents and turning maneuvers, which result in erroneous velocity information, can cause errors in the navigator outputs. The operational constraints imposed by the latter condition are discussed below.

Bounds may be placed upon the earth loop errors by a periodic comparison of position and heading information provided by the inertial navigator with that obtained through celestial observations [Blumhagen, 1963]. Ship's position and heading, as obtained from celestial observations, can be used to accomplish two important tasks. Firstly, the information can be used to "reset" the platform to a new error-free orientation. Secondly, knowing the dynamics of the earth rate loop, the manner in which gyro drift rates propagate into navigation errors allows an estimate of gyro drift rate after the most recent fix [Friedman and others, 1964]. Clearly a gyro drift rate model must be assumed for this to be accomplished. Current drift rate models of high quality gyros assume a bias and a random variation, the random variation containing both stationary and nonstationary components [Dushman, 1962].

One point that is of importance in this connection concerns errors in the celestial observations. In general, the celestial fix is used as a standard against which the navigation and gyro drift rate parameters are compared. However, errors in the fix degrade this process. One can safely assume that over many observations, random errors and their effects will be averaged. However, a bias error is not averaged and, thus, sets the lower bound on the accuracy with which navigation can be accomplished and on the ability of the reset technique to correctly identify and calculate the various drift rate parameters.

A typical curve of navigation error vs. time is shown in figure 3. Error is minimum at the time of the fix and approaches the RMS value of the error in the fix. Because of the imperfectly computed drift rate parameters, compensation does not completely cancel the gyro drifts so that the navigation error begins building up until it is, once again, reduced to the magnitude of the fix error at the time of the next fix.

Where the option exists, it appears reasonable that celestial fixes be performed as often as possible so that the navigation error in the intervening time periods will be small. In some cases this is possible. Sometimes, operational constraints

[5] Referring to the appendix, it can be shown that s_{1i} and s_{2i} are equal when two conditions are satisfied:
(1) The values of minimum slant range along each track are equal, and
(2) the distance between the position of the first beacon interrogation and the position of minimum slant range along each track are equal.

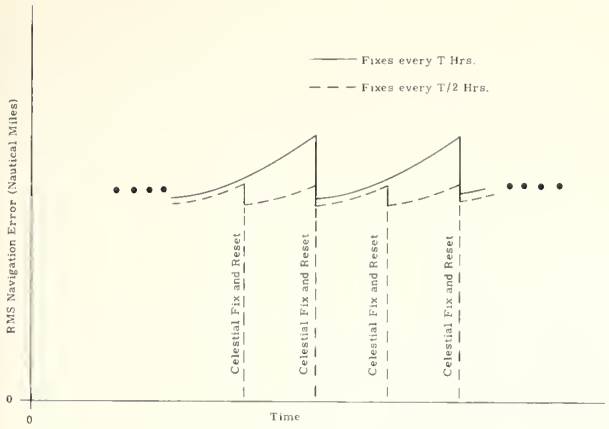

FIGURE 3.—Navigation error as a function of time.

dictate otherwise or make such a mode of operation impractical. Such is the case with the beacon survey. The achievement of a small beacon position error requires pairs of mutually orthogonal tracks, repeated for smoothing purposes. Thus, a more-or-less square pattern is described about the area in which the beacons are deployed.

It is a fact that abrupt turns, of the type under discussion, induce Schuler oscillations in the inertial system. Several explanations for this phenomenon exist. Firstly, since velocity damping of the Schuler loop is provided by the speed log, sideslipping of the ship is not monitored so that during the turn the damping signal is in error. Also, abrupt changes in heading alter the orientation of the inertial system with respect to its binnacle. This is ordinarily a matter of practical significance since cooling air paths, magnetic shielding effects, etc., change as a result of it causing changes in gyro drift rates. The upshot is, simply, that following a turn, Schuler oscillations are induced which, for extremely accurate navigation, preclude use of the inertial system for something on the order of 3 hours (2 periods of the damped oscillation). Although position fixes can be obtained during this period of time and the accompanying resets performed, little is gained. The most practical technique involves, simply, a fix and reset at or near the beginning of each leg of the square.

Using the navigator as described allows some important simplifications to take place in the fundamental error equation, Eq. (12). Most obvious is the fact that if the point of closest approach on each leg of the square is reached at approximately the same time after a reset, then the position errors, $\overline{\delta P^2_{n1}}$ and $\overline{\delta P^2_{n2}}$ are essentially equal. The same is true of the heading errors, $\overline{\delta\theta^2_1}$ and $\overline{\delta\theta^2_2}$.

Of even greater significance is the evaluation of the cross-correlation terms. Thus, where δx_1, δy_1, and $\delta\theta_1$, are the navigation errors in one track past the beacon and δx_2, δy_2 and $\delta\theta_2$ are the errors in the second track of the pair used for a determination of beacon position, it becomes clear that when the navigator is reset at a fixed time prior to the point of closest approach, then

$$\overline{\delta x_1 \, \delta\theta_1} = \overline{\delta x_2 \, \delta\theta_2}, \tag{15}$$

and

$$\overline{\delta y_1 \, \delta\theta_1} = \overline{\delta y_2 \, \delta\theta_2}. \tag{16}$$

Equation (14) can now be rewritten in the following simplified form:

$$\delta P^2_b = \frac{18K^2}{n^2(n^2-1)^2d^2} \sum_{i=1}^{n} (s^2_{1i} + s^2_{2i}) \left[(n+1-2i)^2 + \overline{\delta P^2_n} + R^2_{12}\,\overline{\delta\theta^2}\right] \tag{17}$$

IV. SMOOTHING

As in most realistic applications, several measurements of beacon position must be averaged (smoothed) for the purposes of error reduction. The effect of smoothing is to average the *random* component of beacon position error so that over many measurements it approaches zero. The limit in accuracy is a function of any unknown biases[6] in the measurement equipment. According to the inherent nature of the survey technique, biases in the sonar/beacon equipment are of no consequence. The biases that do contribute to an error in beacon position are those present in the indication of position and heading as provided by the navigation equipment. The principal component of bias in a celestial/inertial navigation mode arises in the indication of position and heading as provided by the star tracker (such as readout errors).

The extension of ship maneuvering for the acquisition of multiple estimates of beacon position is simply a continuation of the single estimate technique, and is illustrated in figure 4. In particular, it is observed that subsequent to obtaining the first estimate of beacon position, each new heading track permits "updating" of the previous

[6]Unknown biases refer to any post-calibration bias residuals.

estimate. The successive estimates thus obtained are *dependent* in that navigation information along the intermediate track is common to both.

To obtain the RMS beacon position error associated with this scheme, it is observed that the estimated components of beacon position, after n tracks have been traversed, are

$$\hat{x} = x_T + \frac{1}{n-1} \sum_{i=1}^{n-1} \delta x_i + B_x \qquad (18)$$

and

$$\hat{y} = y_T + \frac{1}{n-1} \sum_{i=1}^{n-1} \delta y_i + B_y , \qquad (19)$$

where x_T, y_T are the true beacon coordinates, B_x, B_y are the bias components of the error due to the navigation equipment, and δx_i, δy_i are the random errors associated with the estimates derived from tracks (i) and $(i + 1)$. It is additionally noted that n tracks provide n-1 estimates. The MSE's in the estimates $\hat{x}$ and $\hat{y}$ are $\overline{(\hat{x}-x_T)^2}$ and $\overline{(\hat{y}-y_T)^2}$. In formulating these quantities according to Eqs. (18) and (19) there will be the summation of terms of the form $\overline{\delta x_i^2}$, $\overline{\delta y_i^2}$, for $i = 1, 2, \ldots, n-1$, and $\overline{\delta x_i \, \delta y_j}$, $i \neq j$ for $i, j = 1, 2, \ldots, (n-1)$.

With respect to the latter terms, the basis of this estimation technique requires that only those terms where $j = i \pm 1$ are non-zero. With this observation, it follows that

$$\overline{(\hat{x} - x_T)^2} = \frac{1}{(n-1)^2} \sum_{i=1}^{n-1} \overline{\delta x_i^2} + \frac{2}{(n-1)^2} \sum_{i=1}^{n-1} \overline{\delta x_i \, \delta x_{i+1}} + B_x^2 \qquad (20)$$

and

$$\overline{(\hat{y} - y_T)^2} = \frac{1}{(n-1)^2} \sum_{i=1}^{n-1} \overline{\delta y_i^2} + \frac{2}{(n-1)^2} \sum_{i=1}^{n-1} \overline{\delta y_i \, \delta y_{i+1}} + B_y^2 . \qquad (21)$$

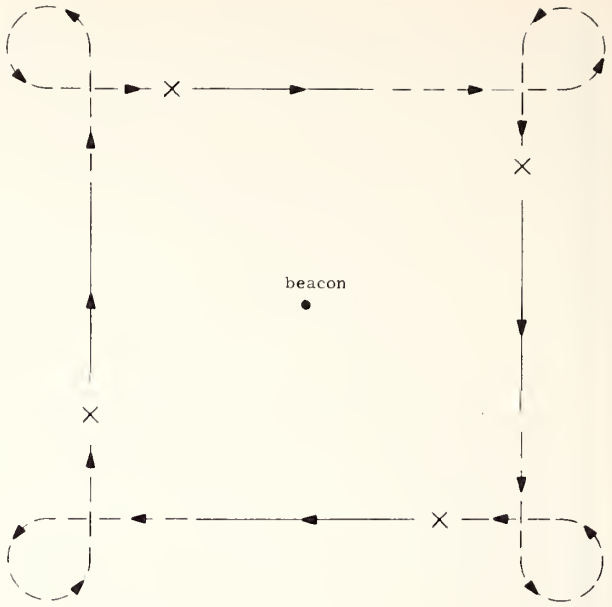

FIGURE 4.—Celestial/inertial navigation geometry for obtaining multiple estimates of beacon position. x = positions where celestial fixes are obtained.

The statistical equivalence of navigation errors from track to track coupled with the assumption that the error induced by echo-ranging noise is relatively invariant from track to track implies that[7]

$$\overline{\delta x_i^2} = \overline{\delta x_{b_r}^2} \; ; \; \overline{\delta y_i^2} = \overline{\delta y_{b_r}^2} \qquad (22)$$

[7]See footnote 5. From the standpoint of survey geometry, the assumption here is that, nominally, the path of the ship forms a square with the beacon at the center.

and $\overline{\delta x_i \, \delta x_{i+1}}$, $\overline{\delta y_i \, \delta y_{i+1}}$ are constant for all i. $\overline{\delta x_{b_r}^2}$ and $\overline{\delta y_{b_r}^2}$ are the mean-square values of the x and y components of beacon position error, respectively. Noting that the sum of Eqs. (20) and (21) is the MSE in beacon position based on n-1 estimates [designated $\sigma^2_b\,(n)$], we have

$$\sigma_b^2\,(n) = \frac{1}{n-1}\,\overline{\delta P_{b_r}^2} + \frac{2}{n-1}\left[\overline{\delta x_k \, \delta x_{k+1}} + \overline{\delta y_k \, \delta y_{k+1}}\right] + B_b^2 \; ; \; 1 \le k \le (n-1) \tag{23}$$

where

$$B_b^2 = B_x^2 + B_y^2 \tag{24}$$

$\overline{\delta P_{b_r}^2}$ is the mean-square value of the *random* error in beacon position based on a *single* estimate. δx_k is the random error in the estimate of the x-coordinate of beacon position as derived from tracks k and $k+1$, and δx_{k+1} is the random error in the estimate derived from tracks $k+1$ and $k+2$. $\overline{\delta x_k \, \delta x_{k+1}}$ is the resultant cross-correlation of these errors. Similarly, $\overline{\delta y_k \, \delta y_{k+1}}$ is the cross-correlation of the respective errors in the y-coordinate of beacon position. These terms can be evaluated using Eqs. (5), (6), and the appropriate modifications to include sonar receiver noise indicated in Eqs. (11a-d). Omitting the intermediate algebra, it can be shown that

$$\overline{\delta x_k \, \delta x_{k+1}} + \overline{\delta y_k \, \delta y_{k+1}} = \frac{1}{2}\left(\overline{\delta\eta^2} + \overline{\delta P_{n_r}^2} + R_{12}^2 \; \overline{\delta\theta^2}_r\right) \tag{25}$$

The terms in Eq. (25) have been described previously. The subscript "r" merely serves to indicate that random errors are involved. Recalling Eq. (17), in conjunction with the assumption that the echo-ranging noise is invariant from track to track, the term $\left(\overline{\delta\eta^2} + \overline{\delta P_{n_r}^2} + R_{12}^2 \; \overline{\delta\theta^2}_r\right)$ is simply the mean-square value of the random portion of beacon position error based on a single estimate, that is,

$$\overline{\delta x_k \, \delta x_{k+1}} + \overline{\delta y_k \, \delta y_{k+1}} = \frac{1}{2}\,\overline{\delta P_{b_r}^2} \tag{26}$$

Hence, substituting Eq. (26) into Eq. (23), the final result is

$$\sigma_b^2\,(n) = \frac{2}{n-1}\,\overline{\delta P_{b_r}^2} + B_b^2 \tag{27}$$

From Eq. (27) it is evident, on a RMS basis, that the limit to which beacon position error can be smoothed is B_b, the bias component. The RMS error in beacon position, normalized to the bias, is given by

$$\frac{\sigma_b\,(n)}{B_b} = \sqrt{\frac{2}{n-1}\,\frac{\overline{\delta P_{b_r}^2}}{B_b^2} + 1} \tag{28}$$

The attendant variation, as a function of the number of tracks taken past the beacon, is illustrated in figure 5.

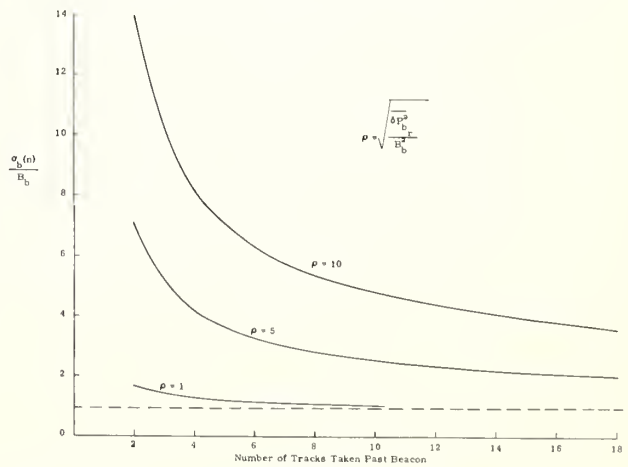

FIGURE 5.—Reduction in normalized RMS beacon position error as a function of the number of tracks.

V. SURVEYING MULTIPLE BEACONS

While the foregoing discussion has been concerned with the survey of a single beacon, the techniques are easily extended to bench marks containing multiple beacons. In general, most beacon navigation systems require two or more beacons.

The required number and optimum geometric configuration of the beacons is, of course, a function of the size, shape and depth of the area to be surveyed as well as the slant range capabilities of both the beacon and the interrogating sonar aboard the ship. These are questions that relate to specific applications and are beyond the scope of this paper. Certain general comments are in order, however.

The quickest and most efficient way to accomplish a survey of several beacons in a given area is to determine the point of closest approach to each of them on each track through the area. This implies that the beacon signals be coded to allow their differentiation. It also implies that the pattern of ship maneuvers be carefully designed to allow an interrogation and response of each beacon on each pass, consistent with the slant range capabilities of the equipments. Since the procedure to be followed in such a simultaneous survey is identical to that described for a single beacon, one can conclude that for a given level of accuracy the same amount of survey time is required. (It is clear, however, that somewhat more time is required for the multiple survey as the length of the individual tracks will probably be larger).

While each beacon can be surveyed, simultaneously, to the same error as is the case in individual surveying, a subtle benefit results from the simultaneous survey when the navigation is provided by an inertial system. The navigation error here is predominantly very low in frequency (84-minute or 24-hour sinusoidal responses to deterministic error inputs). Therefore, if the survey is conducted over a small region, the navigation error contributions at the point of closest approach to each of the beacons are highly correlated. Simply stated, while an error exists in each of the measurements, the errors are of essentially the same magnitude and orientation. The importance of this is that while the uncertainty in locating *each* of the beacons in a simultaneous survey is the same as would occur if separate surveys were conducted, the *relative* locations may be determined much more accurately. This has particular application to those navigation schemes which use the baseline formed by two beacons or a coordinate frame formed by three.

VI. SUMMARY

A technique has been described whereby bottom-moored sonar beacons can be surveyed in absolute position coordinates. The shipboard equipment consists of a sonar transmitter/receiver system to accomplish the necessary echo ranging, and a celestially augmented damped inertial navigator for the purposes of providing ship's position and heading throughout the survey.

The basis of the celestial/inertial navigation mode is developed with particular emphasis placed on constraints imposed by the operational environment (the ocean) and the quality of the measurements.

Finally, the MSE in beacon position (based on multiple estimates) is derived in terms of navigation errors and sonar errors.

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APPENDIX

RMS ERROR IN ESTIMATING THE OCCURRENCE OF THE POINT OF CLOSEST APPROACH

Consider the coordinate system of figure A-1. The η - ξ plane is taken as the plane of the water surface. The η-axis is assumed coincident with the constant heading track taken past the beacon. η_{min} designates the point along the η-axis where *horizontal range* to the beacon is a minimum; ξ_{min} is the corresponding value of the horizontal range.

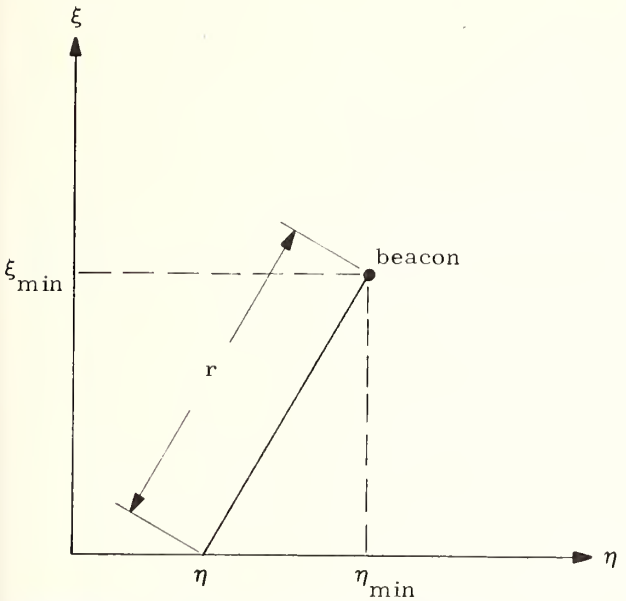

FIGURE A-1.—Range to beacon as a function of distance traveled along constant heading track.

As the ship steams toward η_{min} the horizontal range r at any arbitrary position η is

$$r = \sqrt{\xi_{min}^2 + (\eta_{min} - \eta)^2}. \qquad \text{(A-1)}$$

The *slant range* to the beacon is

$$s = \sqrt{r^2 + z^2}, \qquad \text{(A-2)}$$

where z is the depth of the beacon. Substitution of Eq. (A-2) into Eq. (A-1) provides the slant range as a function of position (relative) along the track:

$$s = \sqrt{s_{min}^2 + (\eta_{min} - \eta)^2}. \qquad \text{(A-3)}$$

As the constant heading track is traversed, the beacon is interrogated periodically by the shipboard transmitter. The measured round-trip times directly indicate the slant ranges to the beacon. An efficient procedure for estimating η_{min}, then, would entail a least-squares fit of the measured data to a curve of the form described by Eq. (A-3). However, rather than deal with a radical, the approach to be adopted here is a least-squares fit of the squared values of measured slant range, that is, subsequent to measuring and squaring the various slant ranges, a least-squares fit of the resultant data is made to the parabola

$$u = u_{min} + (\eta_{min} - \eta)^2 \qquad \text{(A-4)}$$

where $u = s^2$. The validity of this approach is evidenced by the fact that η_{min} is the point at which both slant range and the square of slant range are minimum.

In order to determine the error in the estimate of η_{min} (the error being caused by noise in echo ranging), we first rewrite Eq. (A-4) in the more convenient form

$$u = a_o + a_1 \eta + \eta^2 \qquad \text{(A-5)}$$

where

$$a_o = u_{min} + \eta_{min}^2 \qquad \text{(A-6)}$$

$$a_1 = -2\eta_{min} \qquad \text{(A-7)}$$

The observed value of u_i at position η_i can be written as

$$u_i' = u_i + \delta u_i, \quad i = 1, 2, \ldots n \qquad \text{(A-8)}$$

where

$$u_i = a_o = a_1 \eta_i + \eta_i^2 \qquad \text{(A-9)}$$

δu_i is the error in the observation of u_i as caused by sonar receiver noise and n is the total number of beacon interrogations. To obtain a least-squares fit of the measured data, we minimize the sum square loss function

$$J = \frac{1}{n} \sum_{i=1}^{n} (u_i' - u_i)^2$$

$$= \frac{1}{n} \sum_{i=1}^{n} (u_i' - a_o - a_1 \eta_i - \eta_i^2)^2 \qquad \text{(A-10)}$$

Minimization of J requires solution of the two simultaneous equations

$$\frac{\partial J}{\partial a_o} \equiv o \quad ; \quad \frac{\partial J}{\partial a_1} \equiv o \tag{A-11}$$

from which there results

$$\hat{a}_o n + \hat{a}_1 \sum_{i=1}^{n} \eta_i + \sum_{i=1}^{n} n_i^2 = \sum_{i=1}^{n} u_i' \tag{A-12}$$

$$\hat{a}_o \sum_{i=1}^{n} \eta_i + \hat{a}_1 \sum_{i=1}^{n} \eta_i^2 + \sum_{i=1}^{n} \eta_i^3 = \sum_{i=1}^{n} u_i' \eta_i \tag{A-13}$$

$\hat{a}_o$ and $\hat{a}_1$ are the estimates of a_o and a_1, respectively.

Defining the errors in the estimates of a_o and a_1 as

$$\delta a_o = \hat{a}_o - a_o \tag{A-14}$$

$$\delta a_1 = \hat{a}_1 - a_1 \tag{A-15}$$

and using Eqs. (A-8) and (A-9), Eqs. (A-12) and (A-13) can be written in the form

$$\begin{bmatrix} n & \sum_{i=1}^{n} \eta_i \\ \sum_{i=1}^{n} \eta_i & \sum_{i=1}^{n} \eta_i^2 \end{bmatrix} \begin{bmatrix} \delta a_o \\ \delta a_1 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} \delta u_i \\ \sum_{i=1}^{n} \eta_i \, \delta u_i \end{bmatrix} \tag{A-16}$$

Now, from Eq. (A-7), the error in the estimate of the point of minimum slant range is

$$\delta \eta_{\min} = -\frac{1}{2} \delta a_1 \tag{A-17}$$

Hence, solving Eq. (A-16) for δa_1 and substituting from Eq. (A-17), there results

$$\delta \eta_{\min} = -\frac{1}{2\left[n \sum_{i=1}^{n} \eta_i^2 - \left(\sum_{i=1}^{n} \eta_i\right)^2\right]} \cdot \left[\left(-\sum_{i=1}^{n} \eta_i\right) \sum_{i=1}^{n} \delta u_i + n \sum_{i=1}^{n} \eta_i \, \delta u_i\right] \tag{A-18}$$

The mean-square value of $\delta \eta_{\min}$ is

$$\overline{\delta \eta_{\min}^2} = \frac{1}{4\left[n \sum_{i=1}^{n} \eta_i^2 - \left(\sum_{i=1}^{n} \eta_i\right)^2\right]^2} \cdot \left[\left(\sum_{i=1}^{n} \eta_i\right)^2 \sum_{i=1}^{n} \sum_{j=1}^{n} \overline{\delta u_i \, \delta u_j} + n^2 \sum_{i=1}^{n} \sum_{j=1}^{n} \eta_i \eta_j \overline{\delta u_i \, \delta u_j} - 2n\left(\sum_{i=1}^{n} \eta_i\right) \sum_{i=1}^{n} \sum_{j=1}^{n} \eta_i \overline{\delta u_i \, \delta u_j}\right] \tag{A-19}$$

To evaluate the cross-correlation term $\overline{\delta u_i \, \delta u_j}$, we note that δu_i is the error in u_i caused by the error in the measurement of slant range, δs_i.

Assuming that $(\delta s_i)^2$ is a negligible second-order effect, we can write that

$$u_i' = (s_i + \delta s_i)^2 \cong s_i^2 + 2 s_i \, \delta s_i \qquad \text{(A-20)}$$

Since, by definition, $u_i = s_i^2$, it follows that the error in u_i (i.e., $u_i' - u_i$) is given by

$$\delta u_i = 2 s_i \, \delta s_i \qquad \text{(A-21)}$$

For the purposes of this paper, it will be assumed that the echo ranging noise is stationary and uncorrelated.

Hence

$$\overline{\delta s_i \, \delta s_j} = \begin{cases} K^2 & i = j \\ 0 & i \neq j \end{cases} \qquad \text{(A-22)}$$

where K is the RMS error in the measurement of slant range.

Then, using Eq. (A21),

$$\overline{\delta u_i \, \delta u_j} = \begin{cases} 4 s_i^2 K^2 & i = j \\ 0 & i \neq j \end{cases} \qquad \text{(A-23)}$$

Substituting this result into Eq. (A-19), and simplifying, the expression for the RMS error in the estimate of the point of minimum slant range assumes the form

$$\sqrt{\overline{\delta \eta_{\min}^2}} = \frac{K \sqrt{\sum_{i=1}^{n} s_i^2 \left(\sum_{i=1}^{n} \eta_i - n \eta_i \right)^2}}{n \sum_{i=1}^{n} \eta_i^2 - \left(\sum_{i=1}^{n} \eta_i \right)^2} \qquad \text{(A-24)}$$

Eq. (A-24) can be simplified further if it is assumed that the interval between successive beacon interrogations is constant. Denoting this interval by d, it follows that

$$\eta_i = \eta_1 + (i - 1) d \qquad \text{(A-25)}$$

Then, applying standard series-summing techniques [Dwight, 1947]

$$\sum_{i=1}^{n} \eta_i = n \eta_1 + \sum_{i=1}^{n} (i - 1) d = n \eta_1 + \frac{d}{2} n (n - 1) \qquad \text{(A-26)}$$

$$\sum_{i=1}^{n} \eta_i^2 = \sum_{i=1}^{n} \left[\eta_1 + (i - 1) d \right]^2 = n \eta_1^2 + d \eta_1 \, n(n - 1) + \frac{d^2}{6} n(n - 1)(2n - 1) \qquad \text{(A-27)}$$

Substituting into Eq. (A-24) and simplifying there results

$$\sqrt{\overline{\delta \eta_{\min}^2}} = \frac{6K}{n(n^2 - 1) d} \sqrt{\sum_{i=1}^{n} s_i^2 (n + 1 - 2i)^2} \; ; \; n \geq 2. \qquad \text{(A-28)}$$

Geodetic Methods Applied to Acoustic Positioning

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ABSTRACT

When large-scale bathymetric charting operations are conducted beyond the range of electronic positioning systems, some means of controlling the horizontal positioning of the surveying vessel must be made available. Acoustic transponders implanted on the ocean bottom, by the survey ship, are employed to enable a solution to the positioning problem. The transponders are used in conjunction with a Ships Inertial Navigation System (SINS), and positions obtained by Doppler satellite from the Navy Navigation Satellite System.

The transponders are implanted on the ocean bottom, each with a different preset transponding frequency. Their positions are only generally known. An acoustic network consisting of from three to six transponders is used. The acoustic network is oriented in scale and azimuth by comparisons with the ship's inertial system. The network is oriented on the reference ellipsoid by the many satellite positions which are obtained during the survey operation. The positions of the acoustic transponders are determined by a geodetic adjustment and analysis similar to that used in triangulation and trilateration network adjustment. By using the calibrated transponder network, the survey ship can steam parallel survey lines that are sufficiently fixed in position to construct an accurate bathymetric chart of the ocean bottom.

1. INTRODUCTION

U.S. Naval Oceanographic Office bathymetric charting operations frequently are in ocean areas too remote for the use of conventional surveying systems. Acoustic transponders, used in conjunction with a Ship's Inertial Navigation System (SINS) and satellite fixes made at intervals, make it possible to conduct accurate bathymetric surveys in any accessible ocean area. A transponder network, implanted on the ocean bottom by the survey ship, provides a fixed, though relative, orientation for the ship. SINS is required in the transponder network calibration in order to provide scale and azimuth orientation in the net. Doppler satellite positions are obtained by the survey ship during the survey operation. The satellite positions, when referenced to the transponder net, make it possible to orient the charted area to a given datum on a reference ellipsoid.

Basically, the acoustic system consists of a shipboard transducer, several transponders implanted on the ocean bottom, plus the necessary interface equipment consisting of clocks, digitizers, and an electronic computer [U.S. Navy, 1965]. The system capabilities are such as to permit the simultaneous use of up to six transponders. However, a reasonable and efficient network would likely consist of three transponders forming a figure approximating an equilateral triangle. The sides of the triangle would be from 5,000 to 7,000 meters. Individual transponder depths could vary considerably. The shipboard transducer initiates a signal by transmitting an acoustic impulse at 16 kilocycles per second; at this instant a clock is started for each transponder. The shipboard signal activates each transponder to transmit back at a different preset frequency. The six transponder frequencies may vary from 9.5 to 12 kilocycles per second in intervals of one-half. The responding signals each stops an individual clock on the ship, thus recording two way transmission time to each of the transponders. The system was designed for an accuracy of ± 7 milliseconds, which is equal to about 10 meters.

Considerable acoustic disturbing phenomena occur in the ocean, causing much bad data to be generated. The refraction of sound through water is caused by velocity changes, and it results in a curved transmission path. The error caused by ray bending is ignored since it is usually much less than the system accuracy of 10 meters. It

is sometimes possible for a curved path to take less transmission time than that of a theoretical straight-line path, due to the higher velocity of the curved path [Klein, 1966].

The reflection of acoustic rays results in multiple transmission paths, with of course, different arrival times. Reflections occur at density discontinuities, such as the sea-air boundary, thermal layers in the sea, and the ocean bottom, as well as from schools of fish.

The problem of troublesome sound sources is well stated by Hoover [1966].

> "... the ocean is a noisy place. Random sound is present across the acoustic spectrum. It emanates from waves, rain, wind, fish, and man and his machines. The instantaneous level is often quite high and may be considerably above the level of the signals we hope to receive .... In heavy weather or near human activity, the sound level will be comparable with that found on a city street."

In view of the problem complicating the use of an acoustic network, the technique of employing redundant observations as criteria for detecting and rejecting bad data becomes important. The techniques for the use of multiple observations has been elaborately worked out in conventional triangulation adjustment and analysis computations. The geodetic methods used to solve the acoustic positioning problems of this paper are merely adaptations of the conventional methods.

2. RELATIVE COORDINATE SYSTEM

The selected coordinate system was chosen for computational convenience and for accuracy of data portrayal. The system is a rectangular space system (X,Y,Z), which is oriented in such a way that the X-Y plane coincides with the ocean surface. The Y axis coincides with true north; the X axis coincides with east, and the Z axis is depth. The system is metric in units of meters.

2.1 *Chart Projection.* The X-Y plane is the plane of the chart projection. The error due to the assumption that the X-Y surface is a plane coinciding with the ocean surface amounts to 3 meters over a 10,000 meter distance. The error due to neglecting ocean tides is of the order of 2 meters.

2.2 *Coordinate Transformations.* The geographic coordinates, which may be superimposed on the chart, are assumed to be rectangular in the chart area. This assumption causes errors of less than 3 meters over the chart area.

One of the transponders is designated as the reference transponder (P_R), and coordinates are assigned to it in the following manner.

X_R = 20,000 meters
Y_R = 70,000 meters
Z_R = measured depth
θ_R = assumed latitude
λ_R = assumed longitude

An average radius of curvature for the chart for the meridian *(M)* and for the prime vertical *(N)* are determined by the usual formulas. A mean value of $\overline{X}$ and $\overline{Y}$ for one second of arc is determined for the chart area:

$$\overline{Y} = M \sin 1'' \tag{1}$$

$$\overline{X} = N \cos \theta \sin 1'' \tag{2}$$

The conversion of grid to geographic coordinates is accomplished as follows:

$$\lambda = \lambda_R + (X - X_R)/\overline{X} \tag{3}$$

$$\theta = \theta_R + (Y - Y_R)/\overline{Y} \tag{4}$$

The conversion of geographic to grid coordinate is as follows:

$$X = X_R + (\lambda - \lambda_R)\,\overline{X} \tag{5}$$

$$Y = Y_R + (\theta - \theta_R)\,\overline{Y} \tag{6}$$

3. TRANSPONDER FIX

A transponder fix is defined as that instant of time when the signal is initiated by the ship. Since the ship is underway during the transit time of the signal, each observation is eccentric by a different amount and must be reduced back to the fix time.

The observed quantity for each measurement is the two-way slant range travel time (S):

$$S = S_b + S_b' \tag{7}$$

where S_b is the travel time from the ship to the transponder, and S_b' is the return travel time.

The ship, while making the observation, is on a known course and traverses a known distance. The eccentric correction (ΔS) is computed as follows:

$$\Delta S = S_o - S_o' \approx S_b - S_b' \tag{8}$$

where S_o and S_o' are the computed slant ranges from the approximate coordinates.

The correction is applied as in equation (9).

$$S_b = (S + \Delta S)/2 \qquad (9)$$

4. TRANSPONDER NETWORK CALIBRATION

The network calibration consists of (1) determining adjusted coordinates for each transponder and (2) determining an average velocity for each transponder.

4.1 *Determination of Velocity.* The determination of an average velocity ($\bar{V}$) for each transponder depends upon the observations and computations resulting from an ocean station. A typical ocean station might consist of 24 sample measurements at selected depths. The measurements consist of temperature and a water sample from which to determine salinity. The computation for the average velocity results in a value which is accurate to within 3 meters per second. Sound velocities also can be determined directly at various depths by using a velocimeter [Klein, 1966; USNOO, 1965].

4.2 *Determination of Transponder Depth.* The depth of each transponder, or more exactly the minimum distance between the ship's transducer and the transponder, is determined as the survey ship maneuvers in a clover leaf pattern (Fig. 1).

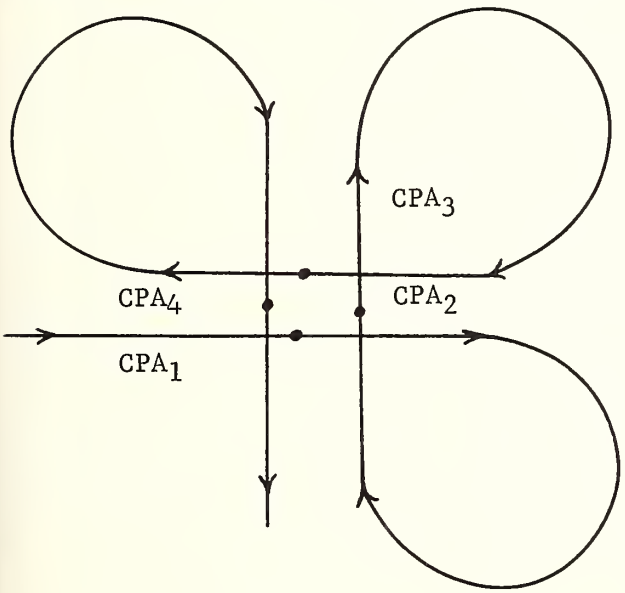

FIGURE 1.—Clover leaf maneuver pattern.

As the ship approaches a transponder a graphic recorder shows a continuous trace of slant-range distance. At the Closest-Point-of-Approach (CPA), the slant range is a minimum for that line. Through a series of CPA values a good value for the minimum slant range can be obtained. The graphic recorder uses an average velocity of 4,800 feet per second for the slant-range distance indication. A value Z for each transponder is therefore computed by equation (10):

$$Z = \bar{V}\,(D/4{,}800) \qquad (10)$$

where $\bar{V}$ is the average velocity for a given transponder determined from the ocean station, D is minimum observed slant range depth.

The value Z is probably accurate to within ± 10 meters. The Z value for each transponder, henceforth is treated as a fixed value.

4.3 *Translation of SINS Lines.* The SINS lines of positions are used to provide scale and azimuth to the network; the resulting values being an average of all SINS lines. An ideal set of SINS lines, on a three station network, would look like figure 2.

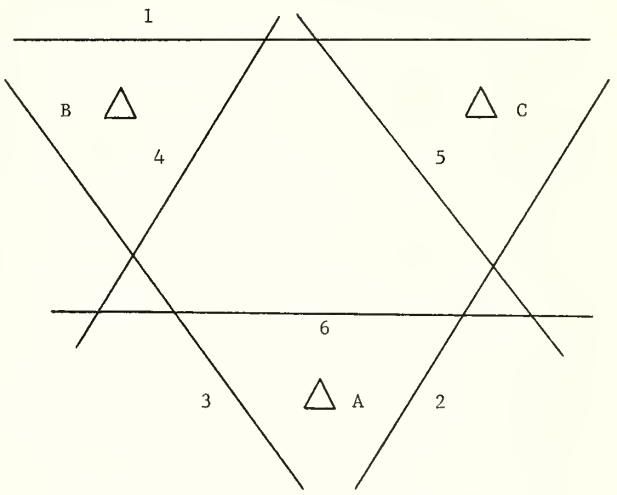

FIGURE 2.—SINS lines of position 1 through 6 for transponders A, B, and C.

Since the SINS position drifts as a function of time, it is natural to expect each SINS line to be on a different and unknown datum. It is assumed that a given line of positions is on one datum. If the line is of a short time duration, this assumption should be valid.

The problem then is to translate each of the 6 SINS lines to the datum of the reference transponder. An x - y translation correction is determined for each line by the method of variation of parameters. The SINS coordinates for the individual fixes are designated as approximate values, (X_o, Y_o, O) and an observation equation is developed for each fix in a given line. The computed distance (S_o) and the observation equations are developed as follows.

$$S_o^2 = (X_o - X_R)^2 + (Y_o - Y_R)^2 + Z_R^2 \quad (11)$$

$$\frac{\partial S_o}{\partial X_o} = \frac{X_o - X_R}{S_o} = a$$

$$\frac{\partial S_o}{\partial Y_o} = \frac{Y_o - Y_R}{S_o} = b$$

$$v = ax + by + S_o - S_b \quad (12)$$

A velocity error or a depth error will have a greater effect on X - Y accuracy for short ranges than it will for long ranges [Palosky, 1965]. Weights (p) for the observations are therefore used. The weights vary from 1 to about 6.

$$p = S^2/Z^2$$

The quantities rendered a minimum are the (pvv) values. The solution for each line is iterated twice, since the original datum may be in error by a large amount. All SINS lines so adjusted are now on the same datum as the reference transponder.

4.4 *Relative Determination of Other Transponders.* In order to determine the positions of the transponders relative to the reference station, the problem is similar to that of an intersected station adjustment. The observation equations are the same as equation (12), with the coefficients being developed for the given station to be adjusted. All 6 SINS lines are used simultaneously in the station adjustment. Figure 2 would result in a strong strength of figure for the determination of the unknown station coordinates.

Figure 3 is an example of an actual transponder network. Six SINS lines were used in the calibration. The reference transponder R is shown, and two error ellipses are shown for transponders A and B. The error ellipses are not drawn to scale, but serve to illustrate the result from poor strength of figure.

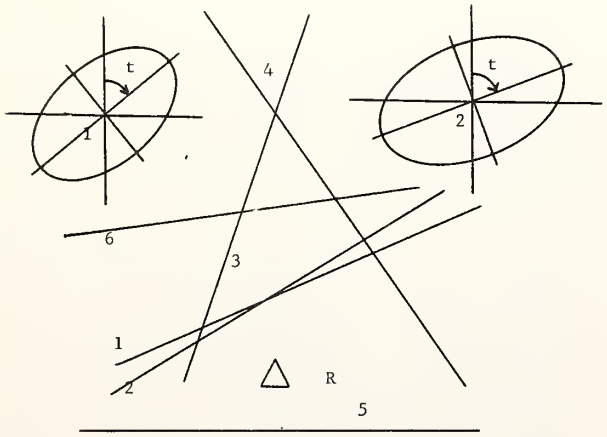

FIGURE 3.—Network calibration example.

An error analysis was included for stations 1 and 2, along with the adjustment. The variance-convariance matrix gave the standard errors (m) for X and Y. The semi-major and minor axis of the error ellipse, A and B respectively are given, also the inclination angle (t) of the ellipse is given.

	Station 1	*Station 2*
mx	± 38 meters	± 57 meters
my	± 39 meters	± 38 meters
A	47 meters	59 meters
B	27 meters	34 meters
t	48 degrees	69 degrees

The station adjustment concludes the network calibration.

5. TRANSPONDER NAVIGATION

Using the transponder system for positioning enables the survey ship to collect data in an orderly manner. The solution of navigation positioning can also serve as an independent analysis of the quality of the calibration. If the calibration is poor, then no amount of data manipulation for positioning will be satisfactory. If the calibration is successful, this is reflected in good agreement in the multiple observations which determine a solution.

From 2 to 6 transponders can be used simultaneously for a unique determination of the ship's position. It is recommended that at least 3 slant ranges be used in the solution. One observation equation, of the same form as equation (12), is developed for each observed slant range. When the standard error is computed for the observations of each fix, this value can be used as criteria for rejecting bad data. In the example network described in Section 4.4, the average of the fix standard error was 45 meters with about 25 percent of the fixes being rejected.

6. DETERMINATION OF ABSOLUTE DATUM FOR CHART

During the course of the survey, satellite fixes are made whenever possible. These fixes are always referenced to the transponder network through the observed slant ranges. The transformation of the grid fix coordinates from the transponders to latitude and longitude gives a direct comparison with the satellite positions. The differences between the two systems in lati-

tude and longitude provides the corrections to place the transponder network on an absolute datum. All that need be done to the chart, to place it on datum, is to shift the geographic tick marks on the chart.

7. CONCLUSION

An acoustic transponder network used in conjunction with SINS and a satellite system can provide sufficiently accurate control for charting operations in any ocean area. Many problems exist in the area of acoustic observations, but by proper employment of redundancies most of these problems can be overcome. If the ship's calibration operation is conducted with care, so as to provide good strength of figure about all stations, system accuracy can be improved. Navigation positioning with the transponder network and an electronic computer can be accomplished on a real time basis, with rejection of bad fixes being made.

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Precise Positioning With a Laser Theodolite

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INTRODUCTION

The coherent light properties of the laser have opened the doors for many practical applications in the field of geodesy and, of more interest to the marine geodesist, in the area of short-range, precise navigation such as that required for inshore hydrographic and oceanographic survey control. While most efforts in applying lasers to geodesy have been in the area of range measurement, this paper deals with both the range and direction measuring capabilities; and in particular, with one automatic instrument capable of measuring both simultaneously. This instrument, ALRADI, an acronym for Automatic Laser Ranging and Direction Instrument, was originally intended as an automatic first-order geodetic instrument, having the direction measuring capabilities of the Wild T-3 Theodolite, and range measuring capabilities as good as or better than the Geodimeter, Tellurometer, and Electrotape, with the added advantage of automatic readout and a single unit, dual purpose instrument. To agencies having these or similar requirements as their prime functions, ALRADI offers many definite advantages.

A high priority project of the U.S. Naval Oceanographic Office is the development of a high-speed, inshore, hydrographic survey system with a quick reaction capability. One of the most important components of this high-speed system will be the positioning subsystem. ALRADI offers one method which could fulfill the requirements both for speed of output and for accuracy.

DISCUSSION

There are two methods used for positioning survey ships and boats—resection and intersection. Resection is the method of determining the vehicle's position by observations (angle or range) taken from the vehicle toward points of known location on shore. Intersection is the method of determining the vehicle's position by observations taken to the vehicle from two or more known positions on shore.

ALRADI, as envisioned, will be able to give continuous positions of survey vehicles operating at speeds of from 50 to 400 knots as proposed for the high speed survey vehicle. It will be able to operate in a hostile environment that would preclude active shore based stations which must be maintained either on a full-time or periodic basis. This system would therefore, of necessity, use the resection method of positioning.

Resection is the preferred method as the observations are made from the survey vehicle where the survey interest is centered. Disadvantages to the resection method of observation usually stem from the fact that a ship is not a stable observing platform. Essentially the instruments or systems currently in use are either of low accuracy, have slow readout capabilities, or require complex and cumbersome logistic support.

High accuracy requirements, therefore, force the use of the intersection method. Intersection takes full advantage of the features of a stable observing platform. Maximum accuracy is possible because of the stability of the observing or transmitting instrument. The major disadvantages of the intersection method are:

1. The observing instruments are not aboard the ship where the actual positioning interest is centered.
2. Usually long-term station occupation and pursuant logistic support is required.
3. Ship-shore radio communication must be established and maintained continually to relay fix and operational control information.

Ship positioning relative to shore control is usually accomplished by one or more of the following instruments or systems. They are listed according to the method in which they are most commonly used.

Intersection

1. Azimuth instrument (1) (4) (5) (8)
2. Theodolite (1) (4) (5)
3. Electrotape (1) (3) (4) (5)
4. Tellurometer (1) (3) (4) (5)
5. Autotape DM-40 (3) (9)

Resection

1. Sextant (4) (5) (6) (8)
2. Pelorus (4) (5) (6) (8)
3. Radar (surveillance) (4) (5) (8)
4. Hydrodist (1) (3) (5) (7)
5. Raydist (1) (3) (5) (7)
6. Shoran (1) (2) (3) (5) (7)
7. Decca (1) (2) (3) (5) (7)
8. Lorac (1) (2) (3) (5) (7)

Numbers in parentheses indicate the most common disadvantages of each instrument or system as indicated below.

(1) Used in a position control system these instruments require three to six men.

(2) Most electronic systems require semi-permanent installations with heavy transmitting equipment, heavy duty generators, antenna fields, personnel camping facilities, and fuel storage. This in turn requires logistic and transportation support by helicopter, landing craft, and/or trucks.

(3) To operate electronic systems in most areas requires prior clearance of broadcast frequencies. This is necessary in order to avoid transmission interference with other electrical activity in the area. Many times long delays in obtaining clearances hold up and considerably raise the cost of operations by the survey team already in the field.

(4) The individual instrument readout rate is too slow to give adequate control for high speed inshore navigation or survey work.

(5) These systems do not have automatic readout recording capabilities. Susceptibility to human recording errors must be considered in later data reduction.

(6) Day and night operations are not always possible.

(7) For most electronic systems, frequent recalibration is necessary.

(8) The azimuth instrument, sextant, pelorus, and surveillance radar are of low accuracy.

(9) Requires shore-based remote instruments which are susceptible in a hostile environment.

ALRADI may be used in both the intersection and resection modes of survey control. Most significant, however, is that *ALRADI is expected to give high accuracy while employed on an unstable platform* (ship, boat, helicopter), in the preferred resection mode.

In the geodetic application, obtaining accuracy is the primary requirement. The ALRADI laser theodolite offers more than one method of measuring range. It can measure range through pulsing, time-delay reading, or phase comparison. Twenty-five-mile ranges and high-order accuracy are already state-of-the-art. Accuracy in measuring direction is the most difficult to obtain with the laser. With ALRADI, readings for azimuth are obtained by swinging a fan-shaped beam in both directions about the axis perpendicular to the direction being measured (figs. 1 and 2). Enough observations must be made to eliminate the effect of scintillation and nonsymmetry of the beam. The same geodetic standards will apply to observations made with ALRADI as are presently applied to theodolite observations. An important feature of this instrument is that it can be completely automatic even to the recording, thereby eliminating the human error factor, one of the largest contributors of error to geodetic observations. The operator need only set up the instrument, level it, and turn it on. After observations are completed he will take out the tape or other recording media used, give it a quick check and move on to the next station.

For inshore surveying using a stable platform, such as a tripod or pillar, the laser theodolite will be set up on a known station ashore and distance and direction will be read to targets on the ship. This method will give maximum accuracy; however, ship guidance requires an additional and often cumbersome ship-shore communications net.

For use on an unstable platform two modes are offered. The first mode is the ultimate in readout rate and accuracy. The second mode offers a wide variety of applications with varying degrees of readout rate and accuracy. The readout rate varies inversely proportional to the accuracy.

Mode I offers continuous readout of both range and bearing. Multiple sets of laser optics are used. A light-seeking unit connected to each set of optics will lock its laser beam to one specific target on the shore. The target can be a retrodirective prism, which would give the strongest return, or any outstanding landmark with good reflectivity. From each set of laser optics, range and bearing would be recorded continuously

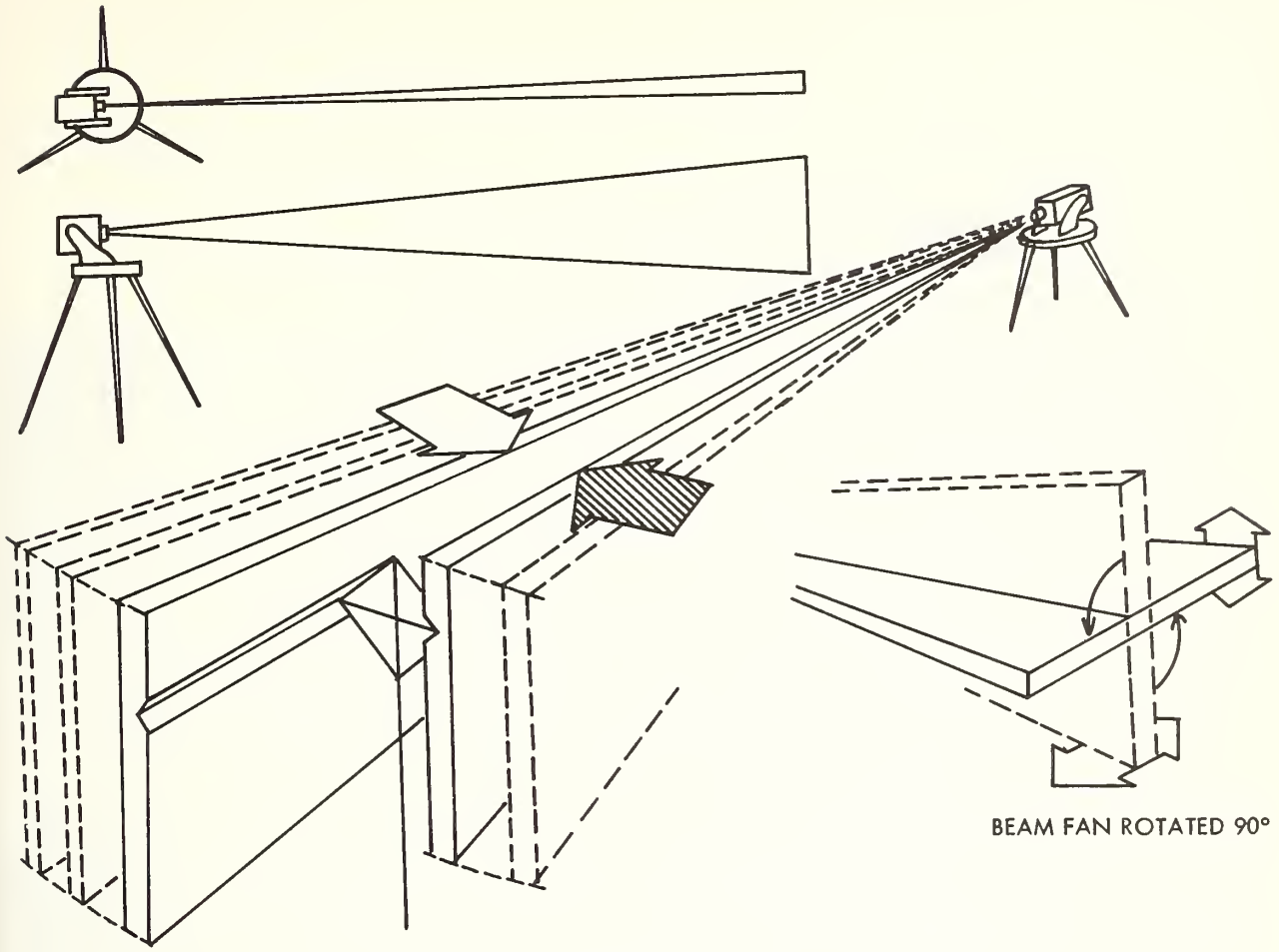
BEAM FAN VERTICAL FOR MEASURING HORIZONTAL ANGLES, SWEEP R/L
BEAM FAN HORIZONTAL FOR MEASURING VERTICAL ANGLES, SWEEP V/D
BEAM FAN ROTATED 90°

FIGURE 1.

so that each movement of the vehicle will be reflected as a change in the readings. With two sets of laser optics locked continuously on as many targets, an extremely accurate position may be obtained. Mode 1 may also be accomplished by installing two single laser instruments aboard ship. By operating with each of these instruments locked on its own target, the same results may be obtained (fig. 3).

Mode II uses the single sweeping fan-shaped beam described for the theodolite. The beam will swing in only one direction. Beam width and scintillation will cause most of the direction inaccuracies. For higher accuracy, a light-seeking unit could be incorporated to center and hold the laser beam on target for longer sampling times (on the order of fractions to 1 or 2 seconds). The slower the angular velocity of the sweep and the longer the lock-on-time, the greater the accuracy; however, the readout rate will be slowed in proportion.

Many laser ranging systems have been or are being developed by various manufacturers. If the direction capabilities of the laser could be demonstrated it should be a relatively simple matter to add the direction capability to a working laser ranger. Funds were made available to the Geodetic Science Department of the Ohio State University for use by the author to attempt to build an instrument which would demonstrate, if possible, this direction measurement capability.

The instrument consisted of several components tied together both mechanically and electrically into an integrated unit. All power requirements were supplied by a 12-volt, direct-current automobile storage battery. The components consisted of the following:

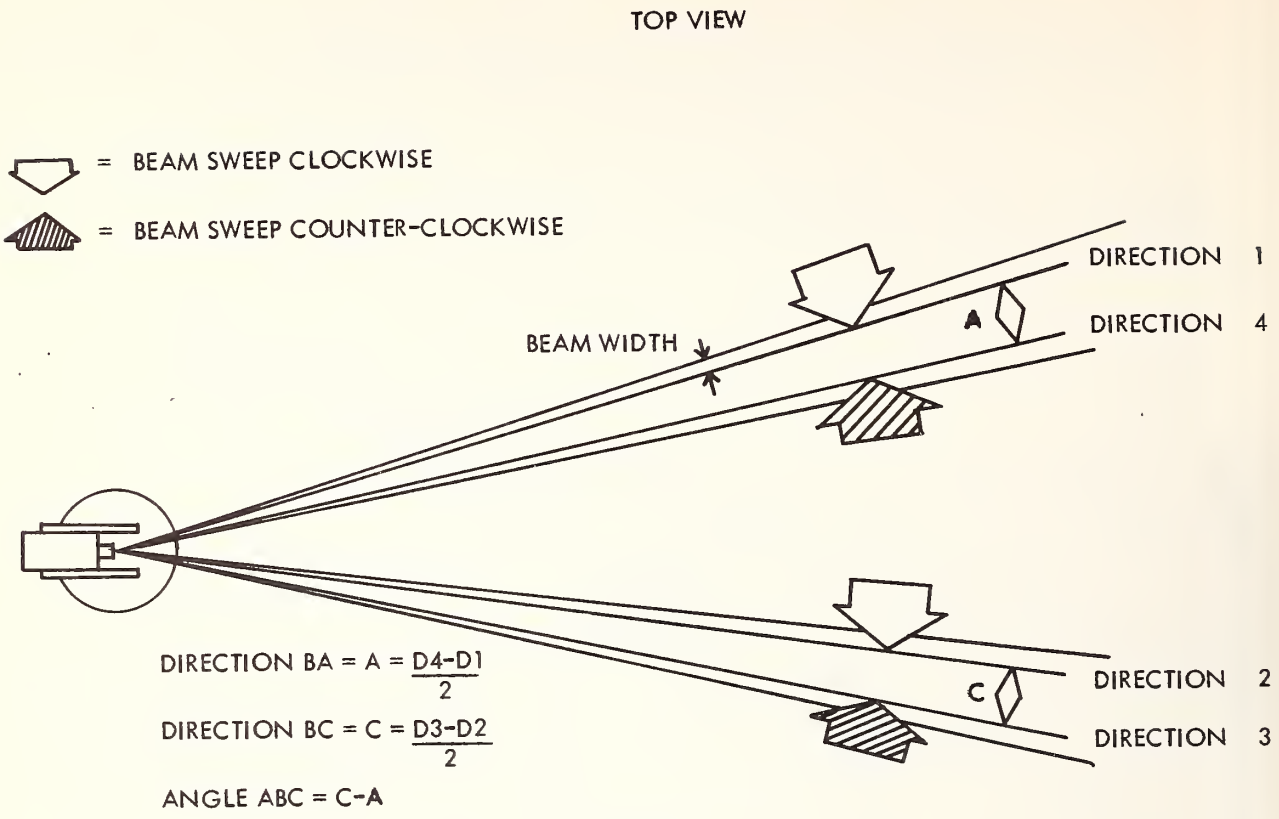

FIGURE 2.

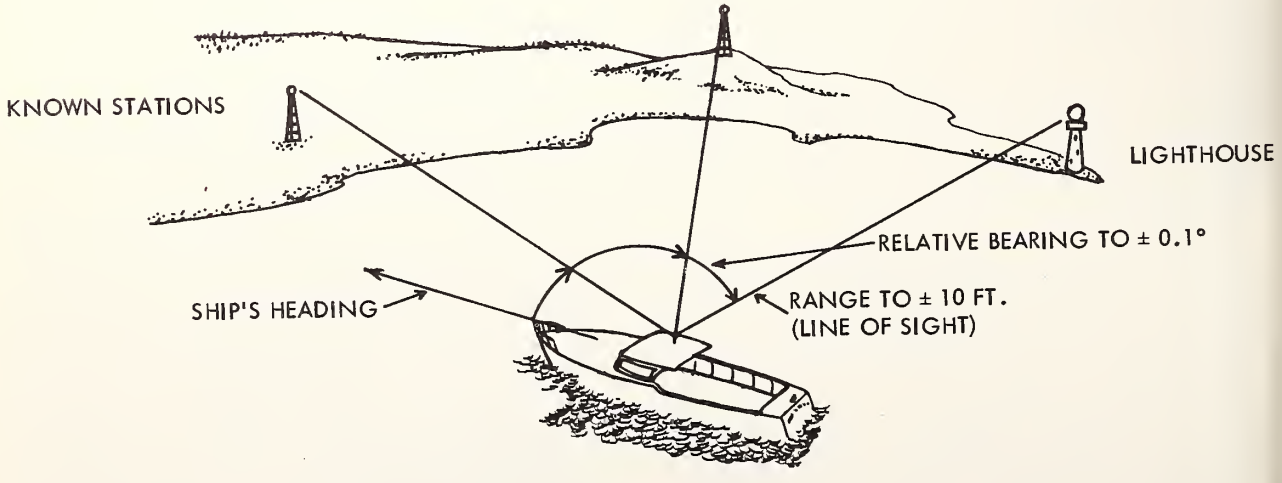

FIGURE 3.

1. Wild-Heerbrugg T-4 Theodolite Base
2. Helium-Neon Gas Laser
3. Laser Power Supply
4. Photomultiplier Tube
5. Photomultiplier Power Supply
6. Optical Interference Filter
7. Beam Splitting and Shaping Optics.

The assembled instrument ready to operate is shown in figure 4.

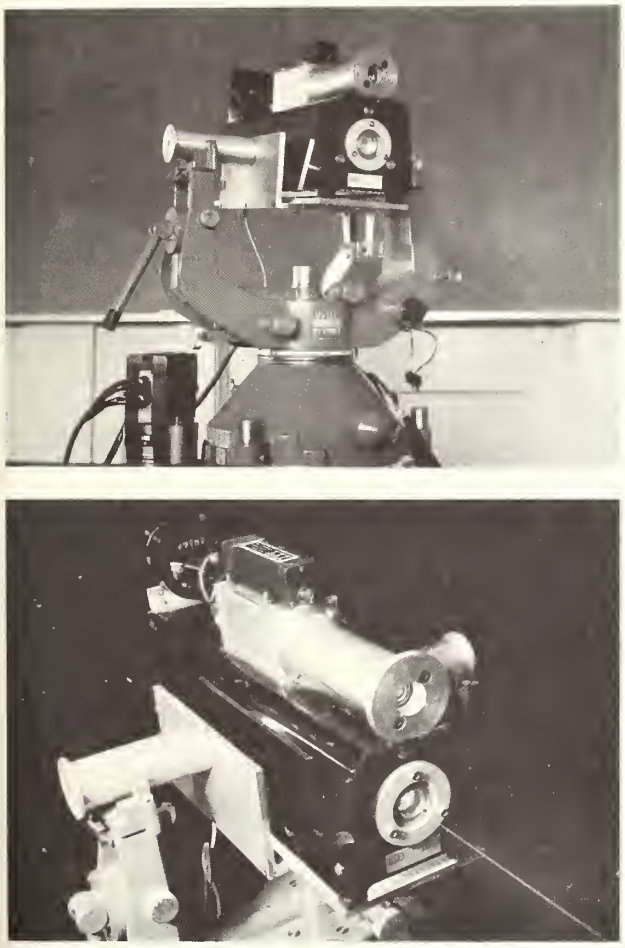

FIGURE 4.

Using this instrument without the beam splitter, and with small mirrors fastened to baseline posts on the O.S.U. baseline at distances of approximately 150 feet from either side of the instrument, and focused so that the reflection was centered on the photomultiplier tube, the results shown in table 1 were obtained. These results were extremely encouraging but pointed out the need for a beam splitter which would direct the returning signal from the retrodirective prisms into the photomultiplier tube automatically.

As the range of the instrument was limited, observations could be made indoors as well as in the field. Thus two targets were set up in the laboratory approximately 15 feet from the instrument. Observations, shown in tables 2 and 3, were obtained during this experiment. At the start of these observations, a power fluctuation was noticed. The needle on the micrometer was not steady, even when the instrument was setting still with the beam holding on the target. Whether the power fluctuation was in the laser output or in the P.M. tube receiver, could not be determined at the time. It was determined later, however, to be in the laser output and was caused by a faulty resistor. This resistor was used to step down the 350 volts from the DC-DC converter to 320 volts for the laser discharge tube, permitting only 280 volts to reach the tube thereby giving a variable output. This power fluctuation plus the difficulty of centering the indicator line in the theodolite horizontal circle prevented more accurate readings. As shown in the tables, however, the observations were quite promising for such short lines and indicated that the instrument held promise of better results.

The first set of observations are shown in table 2. The second set is shown in table 3. After the first six observations in the second group it was noticed that the power fluctuations were not as pronounced as before. The results of a more steady power are very evident in the spread of only 20 seconds recorded in the last ten sets of observations.

The probable error of the mean of each set can be seen in tables 3 and 4. Even though there is quite a large spread in all sets, there is only a difference of 2.4 seconds between the two mean angles.

CONCLUSION

The limited results obtained from this instrument indicate that the laser may be used to make direction measurements. With better optics, for beam collimation in the output, and a good light receiver, such as that used on the geodimeter, it should be possible to develop an instrument capable of making first-order geodetic measurements in both range and direction. This one instrument could then be used for trilateration, triangulation, or traversing of very high order.

The laser beam, although affected by refraction in the same manner as observations through a theodolite, can make the number of observations

Table 1.—Angle Between Posts Using Automobile Mirrors

Inst. Dir.	North Post	Angle	South Post	Observer
C	346-39-42.3		155-42-30.2	Cunningham
C-C	347-01-12.4		155-57-46.7	
Mean	346-50-27.4	168-59-41.0	155-50-08.4	
C	346-40-41.3		155-43-10.6	
C-C	347-00-59.8		155-57-53.9	
Mean	346-50-50.6	168-59-41.6	155-50-32.2	
C	346-40-37.7		155-42-02.2	Reese
C-C	346-58-40.8		155-56-38.9	
Mean	346-49-38.8	168-59-41.8	155-49-20.6	
C	346-41-37.8		155-42-58.0	
C-C	346-58-47.6		155-56-48.4	
Mean	346-50-12.7	168-59-40.5	155-49-53.2	

necessary to mean out this random error. It will have the added advantage of "seeing" through marginal atmospheric conditions such as fog, smog, smoke, and haze, which impede observations with a conventional theodolite.

ALRADI appears to have definite possibilities in both the geodetic field as a range and direction theodolite, and as a precise positioning system for high-speed, inshore, hydrographic survey vehicles.

Table 2.—First Set of Observations in Room Six, Denney Hall

No.	Inst. Dir.	Target #1	Angle	Target #2
	C	18-43-32.0		65-59-23.9
	C-C	18-51-29.9		66-06-31.0
1	Mean	18-47-31.4	47-15-26.0	66-02-57.4
	C	18-43-08.1		65-59-45.8
	C-C	18-51-24.7		66-07-05.9
2	Mean	18-47-16.4	47-16-09.4	66-03-25.8
	C	24-05-45.2		71-20-53.0
	C-C	24-15-23.1		71-30-01.2
3	Mean	24-10-34.2	47-14-52.9	71-25-27.1
	C	24-05-50.9		71-22-09.2
	C-C	24-15-17.9		71-30-13.4
4	Mean	24-10-34.4	47-15-36.9	71-26-11.3
	C	35-05-48.8		82-21-53.8
	C-C	35-15-33.7		82-30-18.3
5	Mean	35-10-41.2	47-15-24.8	82-26-06.0
	C	35-05-41.8		82-20-56.2
	C-C	35-14-19.9		82-30-17.0
6	Mean	35-10-00.8	47-15-35.8	82-25-36.6
	C	45-01-06.4		92-16-48.1
	C-C	45-09-39.9		92-24-24.4
7	Mean	45-05-23.2	47-15-13.0	92-20-36.2
	C	45-00-42.2		92-18-01.9
	C-C	45-09-54.8		92-24-28.5
8	Mean	45-05-18.5	47-15-56.7	92-21-15.2
	C	56-00-21.7		103-16-09.9
	C-C	56-10-00.1		103-23-35.0
9	Mean	56-05-10.9	47-14-41.5	103-19-52.4
	C	56-00-07.9		103-16-08.3
	C-C	56-09-27.1		103-24-00.1
10	Mean	56-04-47.5	47-15-16.7	103-20-04.2
	C	67-49-22.2		115-05-25.7
	C-C	67-59-02.9		115-13-16.6
11	Mean	67-54-12.6	47-15-08.6	115-09-21.2
	C	67-50-21.1		115-05-31.5
	C-C	67-58-42.8		115-14-03.9
12	Mean	67-54-32.0	47-15-15.7	115-09-47.7
	C	78-15-21.4		125-31-16.4
	C-C	78-24-19.1		125-37-59.2
13	Mean	78-19-50.2	47-14-47.5	125-34-37.8
	C	78-13-46.2		125-31-36.6
	C-C	78-24-17.9		125-37-52.3
14	Mean	78-19-02.1	47-15-42.3	125-34-44.4
	C	89-01-35.9		136-19-24.1
	C-C	89-12-05.8		136-26-12.6
15	Mean	89-06-50.8	47-15-57.6	136-22-48.4
	C	89-01-38.6		136-19-21.6
	C-C	89-12-07.2		136-26-19.0
16	Mean	89-06-52.9	47-15-57.4	136-22-50.3

Table 3.—Second Set of Observations in Room Six, Denney Hall

No.	Inst. Dir.	Target #1	Angle	Target #2
	C	100-52-17.3		148-09-19.5
	C-C	101-00-51.4		148-15-56.1
1	Mean	100-56-34.4	47-16-03.4	148-12-37.8
	C	100-52-12.5		148-08-04.7
	C-C	101-01-33.5		148-15-48.4
2	Mean	100-56-53.0	47-15-03.6	148-11-56.6
	C	111-49-30.7		159-06-16.6
	C-C	111-59-27.6		159-13-49.1
3	Mean	111-54-29.2	47-15-33.6	159-10-02.8
	C	111-49-41.0		159-05-31.2
	C-C	112-00-09.4		159-13-52.4
4	Mean	111-54-55.2	47-14-46.6	159-09-41.8
	C	122-51-48.8		170-07-52.8
	C-C	123-01-21.7		170-15-26.0
5	Mean	122-56-35.2	47-15-04.2	170-11-39.4
	C	122-51-56.0		170-09-16.6
	C-C	123-01-27.4		170-16-23.4
6	Mean	122-56-41.7	47-16-08.3	170-12-50.0
	C	134-54-18.4		182-10-18.7
	C-C	135-03-01.2		182-18-06.2
7	Mean	134-58-39.8	47-15-32.6	182-14-12.4
	C	134-54-21.2		182-10-28.9
	C-C	135-03-03.0		182-18-06.2
8	Mean	134-58-42.1	47-15-35.5	182-14-17.6
	C	145-51-11.1		193-07-11.7
	C-C	146-00-12.6		193-15-06.3
9	Mean	145-55-41.8	47-15-27.2	193-11-09.0
	C	145-51-04.0		193-06-53.2
	C-C	146-00-06.9		193-15-02.6
10	Mean	145-55-35.4	47-15-22.5	193-10-57.9
	C	156-51-12.4		204-07-22.7
	C-C	157-00-05.6		204-15-13.1
11	Mean	156-55-39.0	47-15-38.9	204-11-17.9
	C	156-51-23.6		204-07-36.8
	C-C	157-00-01.3		204-15-04.1
12	Mean	156-55-42.4	47-15-38.0	204-11-20.4
	C	167-51-25.0		215-07-25.7
	C-C	168-00-08.6		215-15-01.8
13	Mean	167-55-46.8	47-15-27.0	215-11-13.8
	C	167-51-05.5		215-06-55.3
	C-C	168-00-15.1		215-15-03.0
14	Mean	167-55-40.3	47-15-18.9	215-10-59.2
	C	179-46-46.0		227-02-42.2
	C-C	179-55-22.5		227-10-23.9
15	Mean	179-51-04.2	47-15-28.8	227-06-33.0
	C	179-46-39.7		227-02-41.1
	C-C	179-55-22.6		227-10-23.2
16	Mean	179-51-01.2	47-15-31.0	227-06-32.2

Table 4.—Computation of the Mean and Probable Error of the Mean for First Set of Observations

Angle			v	
°	'	"	"	
47	15	26.0	-00.4	
	16	09.4	43.0	Mean Angle = 47° 15' 26".4
	14	52.9	-33.5	
	15	36.9	10.5	$[vv] = 10492.40$
	15	24.8	-01.6	
	15	35.8	08.4	Probable Error of the Mean m
	15	13.0	-13.4	
	15	56.7	30.3	$m = \pm .6745 \sqrt{\frac{[vv]}{n(n-1)}}$
	14	41.5	-44.9	
	15	16.7	-09.7	
	15	08.6	-17.8	$m = \pm .6745 \sqrt{\frac{10492.40}{16(15)}}$
	15	15.7	-10.7	
	14	47.5	-38.9	
	15	42.3	14.1	$m = \pm (.6745)(6.612)$
	15	57.6	31.2	
47	15	57.4	31.0	$m = \pm 4".5$

Table 5.—Computation of the Mean and Probable Error of the Mean for Second Set of Observations

Angle			v	
°	'	"	"	
47	16	03.4	34.6	
	15	03.6	-25.2	Mean Angle = 47° 15' 28".8
	15	33.6	04.8	
	14	46.6	-42.2	$[vv] = 6195.81$
	15	04.2	-24.6	
	16	08.3	39.5	$m = \pm (.6745)(5.081)$
	15	32.6	03.8	
	15	35.5	06.7	$m = \pm 3".4$
	15	27.2	-01.6	
	15	22.5	-06.3	
	15	38.9	10.1	NOTE:
	15	38.0	09.2	For the last ten sets, $m = \pm 1".35$
	15	27.0	-01.8	
	15	18.9	-09.9	
	15	28.8	00.0	
47	15	31.0	02.2	

Marine Gravity Surveying Instruments and Practice

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The acquisition of gravity data has proceeded at an ever increasing rate since the time of Galileo and his famous, but discredited, Leaning Tower of Pisa experiment. Encouraged by mining engineers, geophysicists, and geodesists, remarkable strides have been made in gravimetry in recent years; particularly noteworthy are the achievements in marine gravimetry during the past decade. Marine gravity surveys were successfully accomplished by Vening Meinesz in the 1920's after development of his three-pendulum apparatus. Data were obtained aboard submarines of the Netherlands, and subsequently by J. Lamar Worzel of the Lamont Geological Observatory aboard British and American submarines. Although the data were remarkably reliable, progress was extremely slow. The introduction of underwater gravity meters in 1946, forerunners of the meter used by the USC&GS ship *Bowie* in 1962 to establish the San Francisco gravity range (fig. 1), and shipboard models in 1957, such as the LaCoste and Romberg Air-Sea gravity meter (fig. 2), ushered in a new era in marine gravimetry.

With improved underwater meters, surveys can be conducted to depths of 3,000 and 4,000 feet. Optimum accuracy at the observation site is 0.02 mgal which is equivalent to the accuracy attained by land meters. Under the most adverse operating conditions an accuracy of 0.1 mgal is claimed. Such data are well within most geodetic and geophysical requirements. Difficulties ensue when these data are reduced to sea level. The lack of tidal, gravity gradient, and depth information and errors in determining the positions of the submerged point and its corresponding surface reference are among the prime problems. For example, hydrographers state that depths can only be determined to one percent of recorded values; for depths of 3,000 feet a 1.6 -mgal error would be introduced into the reduction to sea level in regions such as the abyssal plains and larger errors could be expected over canyons and trenches where the terrain correction may never be known. However, effective use has been made of underwater gravity meters on the continental shelf for mineral exploration. Free-air anomaly charts, similar to those prepared by the U.S. Coast and Geodetic Survey for the regions from Cape Hatteras to Cape Henry (fig. 3) and from Cape Henry to Cape May (fig. 4) have been used for oil exploration. Recently the Coast and Geodetic Survey and other organizations have established gravity ranges on the continental shelf for the evaluation of shipboard gravity meter systems. Such ranges, in the western hemisphere, have been established in the vicinity of San Francisco, in Oregon coastal waters, near Halifax, N. S., off the coast of Rhode Island, and

FIGURE 1.—Underwater meter lowered from USC&GS ship *Bowie*.

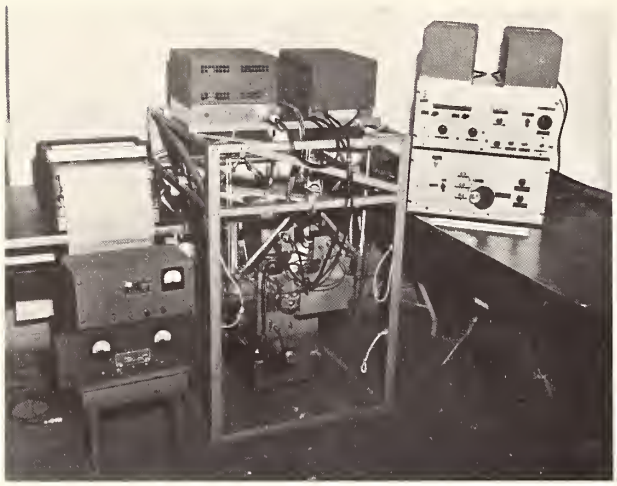

FIGURE 2.—LaCoste and Romberg Air-Sea Gravity Meter (gimball mounted).

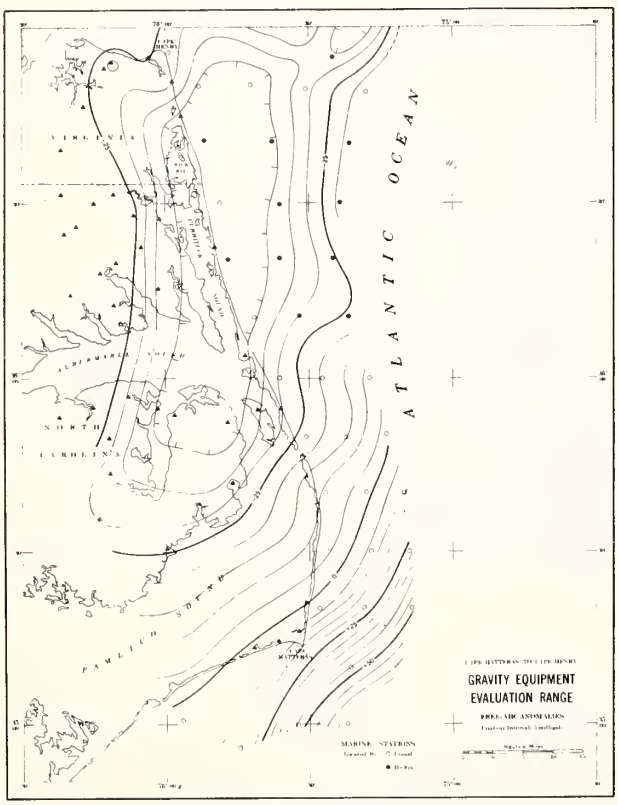

FIGURE 3.—Gravity Range—Cape Hatteras to Cape Henry.

in the vicinity of Norfolk, Va. (fig. 5). Generally, stations are observed at 3-mile intervals with additional stations observed where the gravity gradient departs from linearity. The continental shelf program of the Coast and Geodetic Survey calls for stations at approximately 10-mile intervals out to the 100-fathom curve. Such a survey is being carried out from Cape Cod to

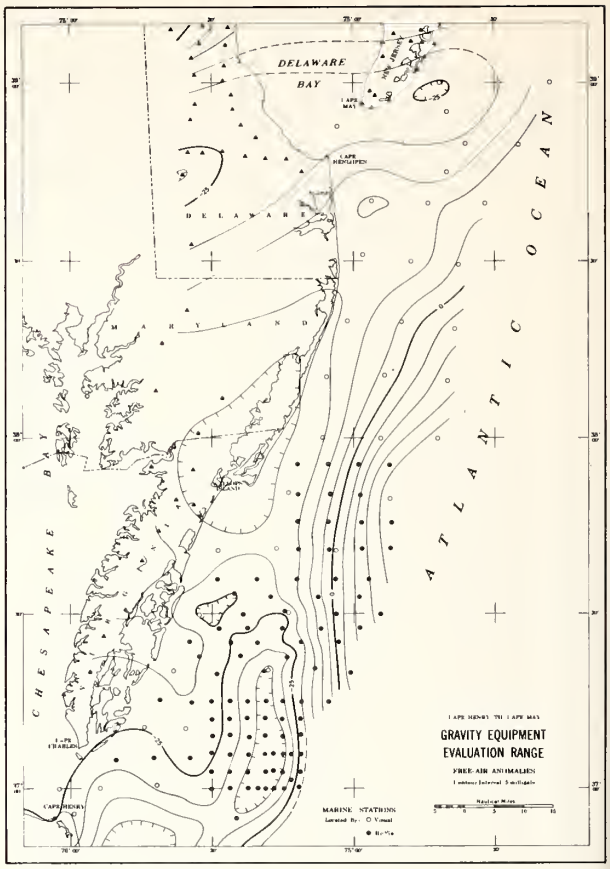

FIGURE 4.—Gravity Range—Cape Henry to Cape May.

northern Maine. Eventually, accurate data will be available over all shelf regions to permit an operating mode evaluation of shipboard gravity systems upon entering or departing any port; that is, if the navigation problem can be resolved.

For shipborne gravity meter operations, it is assumed that ship accelerations are of much higher frequency than the gravity variations. Therefore, a suitable low-pass filter should attenuate the disturbing accelerations and permit normal gravity variations to pass. Filtering is accomplished through heavy damping, hundreds of times greater than critical, of the gravity sensing element plus either electronic or digital filtering, or both, of the signal generated by any displacement of the sensing element from a null position. The LaCoste and Romberg meters employ air damping, the Japanese and Soviets oil damping, and the Askania and Bell Aerosystem magnetic damping of the sensing element. Electronic filtering of the sensing element signal is used by LaCoste and Romberg, the Soviets, and Askania, and digital filtering by the Japanese and Bell Aerosystem. If only oscillatory vertical accelerations are encountered, this procedure is quite straight forward and does result

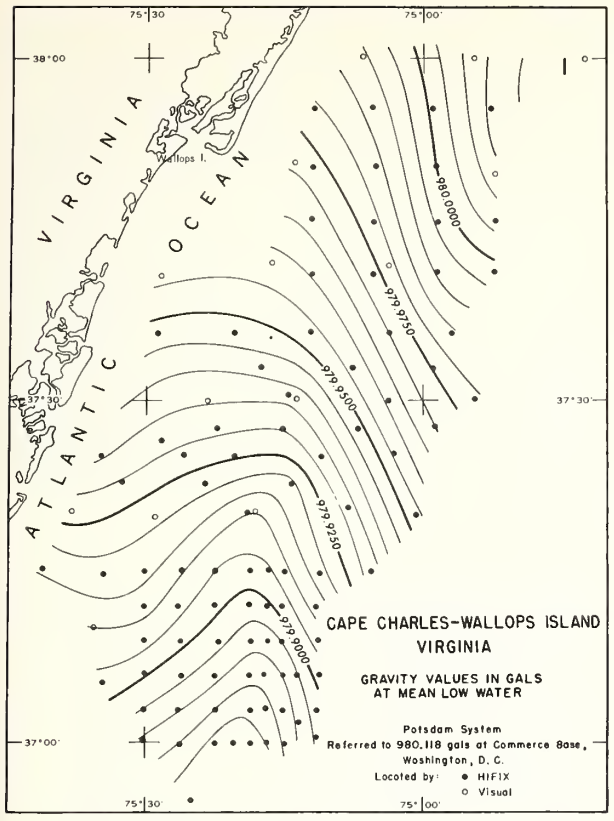

FIGURE 5.—Cape Charles-Wallops Island Gravity Range.

in accurate values over an interval equal to the filtering period and the time constant of the gravity measuring system.

To demonstrate the response of a heavily damped sensing element, a gravity gradient of 10 milligals per nautical mile was simulated in the laboratory. The response, for maximum electronic filtering, lagged the simulated change by approximately 5 minutes; this is the time lag which results from the filtering normally chosen for ocean surveys. The lag could have been reduced by choosing a shorter filtering period. A five-minute displacement of the response curve (fig. 6a) shows excellent agreement with the simulated change with only minor discrepancies for the initial readings, for the readings at the bottom of the trough, and for the readings approximately 10 minutes after again reaching the top of the trough. Although the sudden changes simulated at these points are rare, one should expect such behavior for large gravity gradients. In such instances extreme care must be exercised in interpreting the data. It is interesting to note that this profile would be obtained by a ship traversing a 10-mgal/nm gravity gradient at a speed of six knots, if all extraneous accelerations were attenuated. Traversing the same feature at 12 knots (fig. 6b) would produce larger discrepancies, but only at the bottom of the trough would the data be unacceptable. With the emphasis upon increased ship speed, a simulated traverse of the trough at 18 knots was attempted (fig. 7a). It is evident that these data are unacceptable as observed. Reducing the electronic filtering to a minimum, which results in a time lag of 2 minutes, increases the reliability of the data (fig. 7b), but this reduced averaging

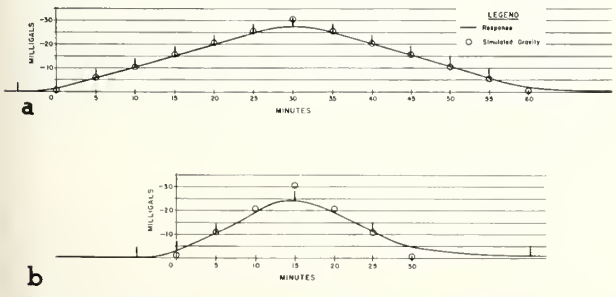

FIGURE 6.—Profile obtained by a ship traversing a simulated 10 mgal/nm gravity gradient at a speed of 6 knots *(a)* and 12 knots *(b)*.

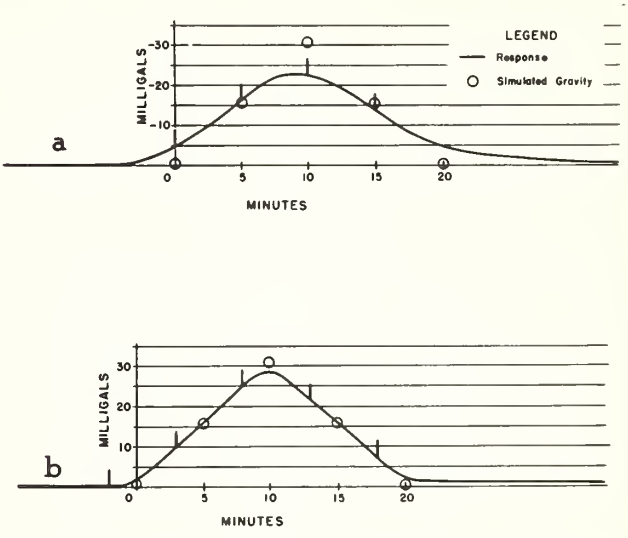

FIGURE 7.—Profile obtained by a ship traversing a simulated 10 mgal/nm gravity gradient at a speed of 18 knots with maximum damping *(a)* and minimum damping *(b)*.

time is hardly feasible under normal operating conditions. There is nothing startling in these data to the marine gravimetrist; only a warning to the analyst and the user. There is also a challenge to the developers of marine gravity meters. Can one reduce the damping, making the meter more sensitive to gravity variations and reducing the time lag, and still attenuate all extraneous accelerations?

Thus far, we have considered only accelerations along the vertical axis. However, when making observations on a moving platform, the gravity sensing element can have six degrees of

freedom; translations caused by heave, surge, and sway and rotations caused by roll, pitch, and yaw. One or more of these motions can be suppressed by constrainment of the sensing element. LaCoste has shown that minimum constrainment is required in the lateral plane if the sensing package is gimbal mounted (fig. 2) and therefore free to align itself with the total acceleration vector. This resultant acceleration is reduced to the true acceleration by applying a correction which is a function of the angular displacement of the sensing package with respect to the true vertical. The first nineteen marine meters produced by LaCoste and Romberg were gimbal mounted and, where accelerations were in the ± 50 gals range, the results were acceptable. The Graf-Askania and the Soviet GAL gravimeters may also be mounted on a Cardan suspension, but the results have been disappointing.

Recently LaCoste and Romberg has used a system stabilized in the vertical direction (fig. 8)—following the lead of Graf-Askania (fig. 9), Japan (fig. 10), and Bell Aerosystem (fig. 11).

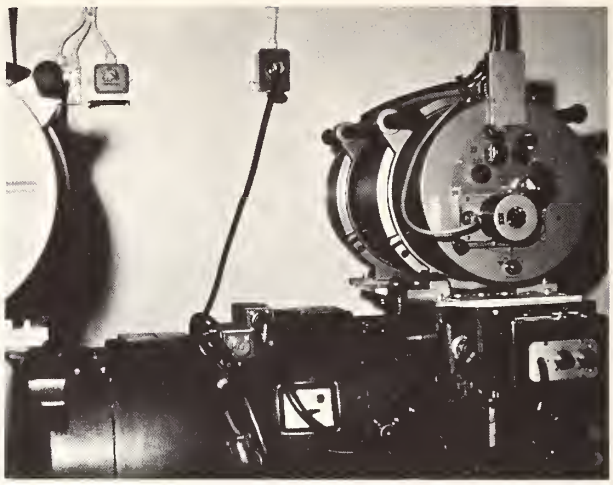

FIGURE 9.—Askania Seagravimeter (Anshultz stable table).

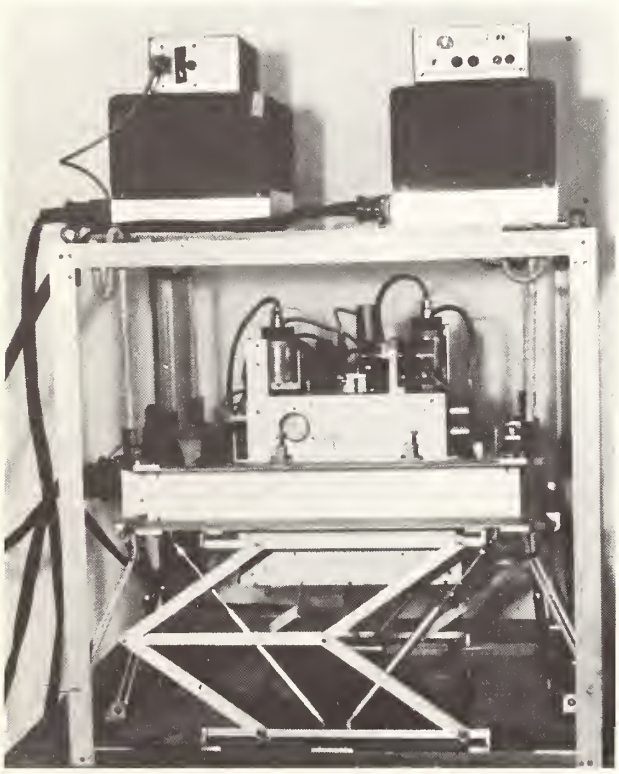

FIGURE 8.—LaCoste and Romberg Air-Sea Gravity Meter (stable table mounted).

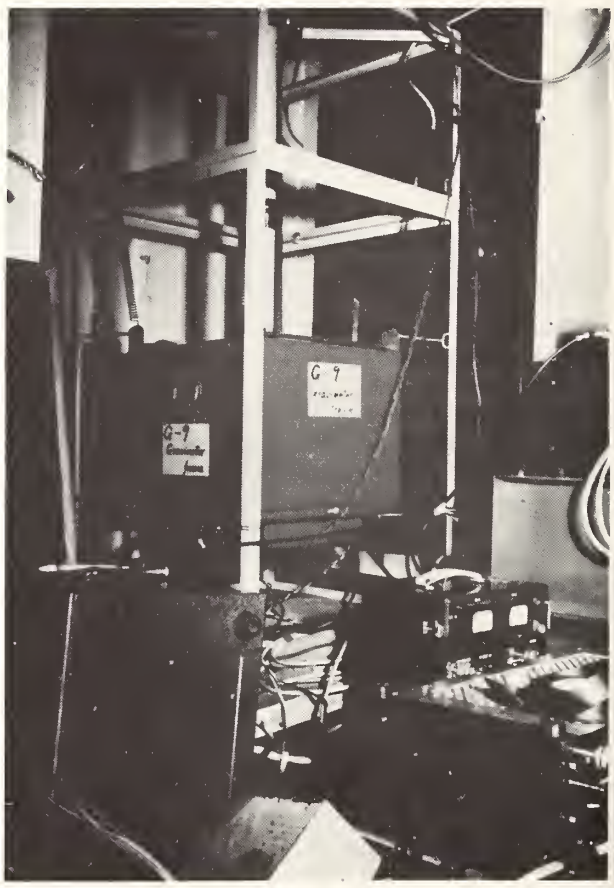

FIGURE 10.—Japanese gravity meter.

These stabilized systems minimize the effect of horizontal accelerations and have proven to be more accurate than the gimbal mounted systems at the high accelerations normally encountered. In addition to heavy damping the sensing element is supported with stiffened fibers or springs in the lateral direction restraining it to movement in a vertical plane. These systems attempt to maintain the sensing element at a null position thereby reducing the effect of cross-coupling; the result of interaction between vertical and horizontal

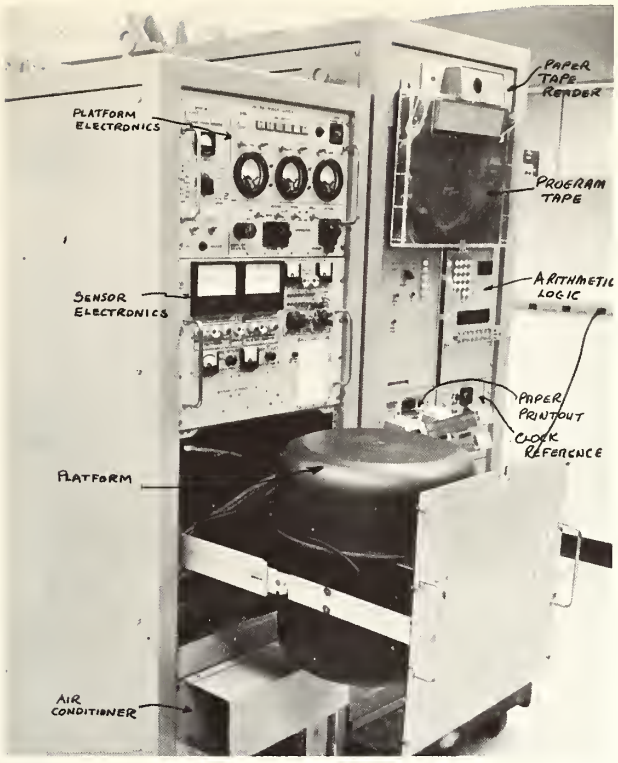

FIGURE 11.—Bell Aerosystem Gravity Meter.

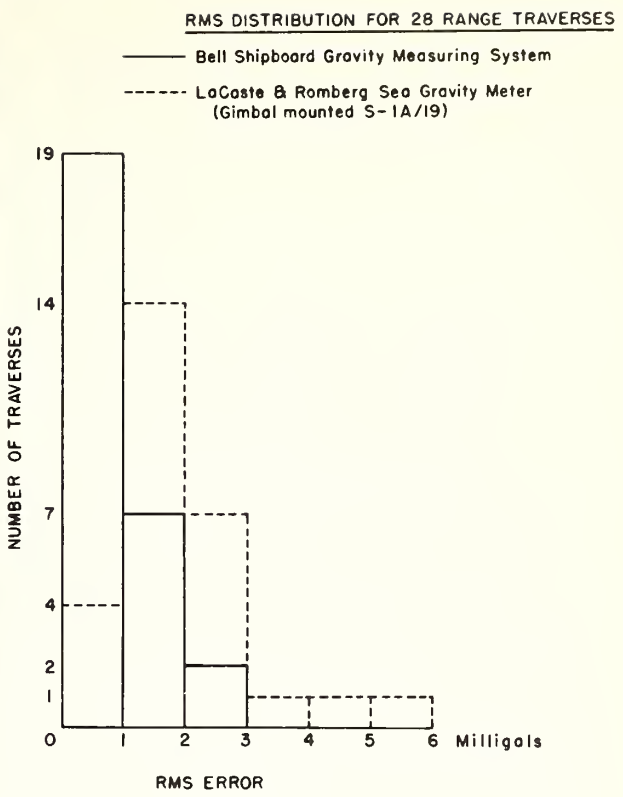

FIGURE 12.—RMS distribution—Bell and LaCoste and Romberg Meters.

accelerations. The Bell and LaCoste and Romberg stabilized meters incorporate corrections for cross-coupling in their systems and Askania contemplates doing the same. Stabilized systems are also subjected to errors due to off-level and to periodic motion of the stabilized table.

The accuracy of these systems is evident from operations over known gravity ranges. For example, the Bell, the LaCoste and Romberg gimbal mounted, and the Askania meters have recently been tested over the Cape Charles, Va., gravity range. A comparison of the Bell and the LaCoste and Romberg gimbal-mounted meters (fig. 12) indicates a slight advantage for Bell; but the Bell system operated at larger accelerations and with greater accuracy. Table 1 presents the point by point comparisons with adopted range values for each system.

The data over lines where accelerations exceeded 50 gals are given in table 2. Accelerations during the test were observed and recorded from the voltmeters on the control panel of the Bell meter. Accelerations were also computed from the LaCoste and Romberg beam and horizontal accelerometer records. Vertical acceleration corrections were applied on lines 19 and 21; the correction was not significant for the other lines. Considering the sea states, both systems achieved acceptable performance levels. The errors are those marine gravimetrists have learned to expect even in regions of accurate navigational control.

In August 1966 Askania Seagravimeters 22 and 23 were field tested aboard the USC&GS ship *Oceanographer*. These meters were mounted on Anshultz electrically erected vertical gyroscope tables back-to-back to provide data on the cross-coupling effect. Later models of Askania meters will be designed to maintain the sensing element in the horizontal direction by off-leveling the table, thereby eliminating any cross-coupling. The root mean square error was less than ± 4 mgals (fig. 13) on each traverse of the Cape Charles, Va., gravity range. Vertical and horizontal accelerations during this test aboard the USC&GS ship *Oceanographer* were considerably less than those experienced by the Bell and the LaCoste and Romberg systems aboard the USNS *Sgt. Curtis F. Shoup*. The drift determined for meter 23 is in doubt; the reduction was carried out with and without drift correction. The distribution of errors in table 1 would indicate that the drift should not be applied. But, if the differences between 22 and 23 are due to cross-coupling, mean values should be used; our statistics then indicate that the drift should be applied. During these tests it was noted that 15 to 20 minutes were required before valid gravity data could be

obtained after a major course change. These meters are also critically affected by temperature changes of more than 2° C.

For these operational tests, ships traverse the gravity range along 10- to 15-mile lines spaced at 22.5; the pattern resembles the spokes of a cartwheel. Navigation is accurately controlled with position fixes at 1, 3, or 5-minute intervals and one or more marker buoys provide position check points on each traverse. Course with respect to the ground and speed are kept constant over each line.

In an article to be published in *Geophysics*, LeFehr and Nettleton report (fig. 14) extremely fine results for a LaCoste and Romberg gravity meter mounted on a stabilized platform. The meter was tested aboard a 100-foot vessel over a known gravity field about 20 miles southeast of Freeport, Texas. The authors state that position uncertainties could not account for more than 0.2-mgal errors in the final results. Unfortunately, a datum shift of 7 or 8 milligals was required to adjust the observed data to the underwater reference datum. The maximum discrepancy of 2.5 mgals at one of 25 intersection points indicates the consistency of the survey.

Allowing for a one-milligal uncertainty in range values, with reliable navigational control and accelerations under 150 gals, data from stabilized systems give a mean square error of ± 3 mgals or less where the gravity gradient is small; point values may be in error by as much as 6 mgals. Generally, these extremes are difficult to detect and therefore must represent the minimum discrepancies to be expected. Geodesists and geophysicists could learn to live with such data, but they are barely attainable under the best of conditions.

With advanced marine gravimetry the major problems at sea are: (1) the maintenance of con-

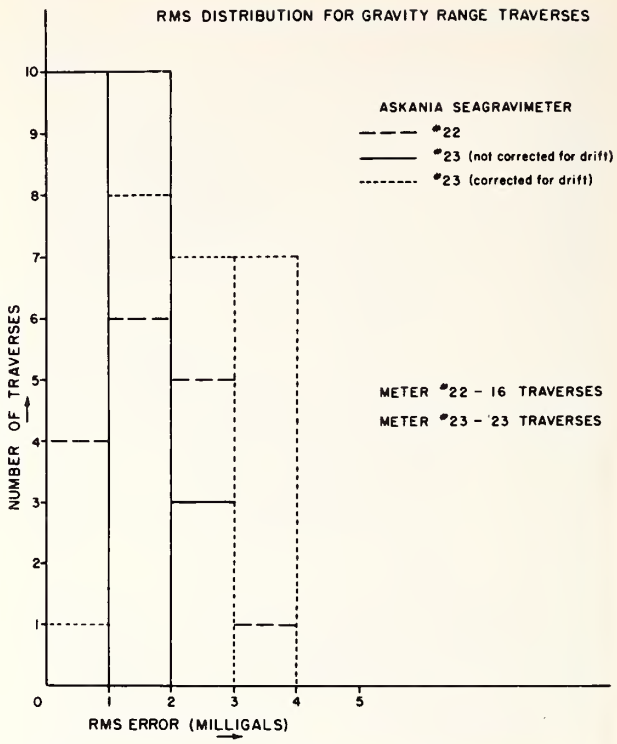

FIGURE 13.—Evaluation of Askania Seagravimeters.

Table 1.—Comparison of Gravity Range and Gravity Meter System Values

Discrepancy *(mgal)*	Bell	LaCoste (gimbal)	Number of observations Askania				
			22*	23^{α}	23	$\frac{(22^*+23^{\alpha})}{2}$	$\frac{(22^*+23)}{2}$
0 to 1.0	373	203	59	139	50	97	106
1.1 to 2.0	111	138	55	67	72	40	34
2.1 to 3.0	20	88	27	23	68	13	9
3.1 to 4.0	16	32	9	5	32	1	2
4.1 to 5.0	11	14	2	2	12		
5.1 to 6.0	4	6	1		1		
6.1 to 7.0	2	2			1		
7.1 to 8.0		5					
8.1 to 9.0		6					
9.1 to 10.0		2					
10.1 to 11.0		2					
Total obs.	537	498	153	236	236	151	151

*zero drift.
$^{\alpha}$drift not applied.

Table 2.—Comparison of LaCoste (gimbal) and Bell Systems Subjected to Large Accelerations

Line	Average acceleration		Surge acceleration		Number of observations		Largest error		MSE	
	Vertical *(gals)*	Horizontal *(gals)*	Vertical *(gals)*	Horizontal *(gals)*	Bell	LaC	Bell	LaC	Bell	LaC
18	38	65	50-60	100-140	5	5	- 2.5	- 3.6	± 1.4	± 2.7
19	80	88	150-275	120-250	40	19	+6.6	- 9.7	± 3.0	± 2.5
21	60	78	80-150	100-160	41	43	+6.7	- 10.4	± 1.8	± 4.6

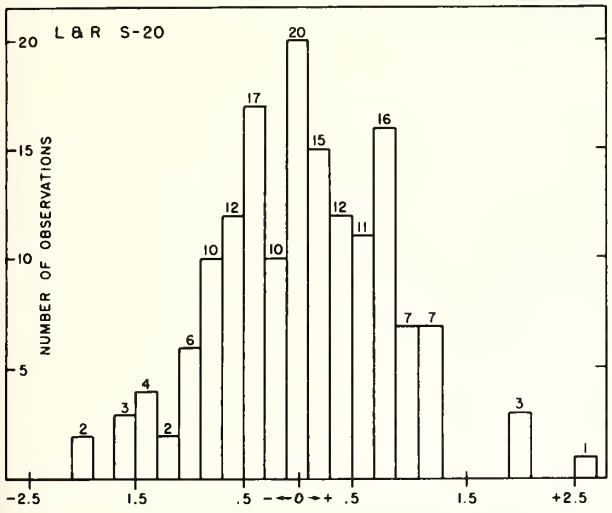

FIGURE 14.—Errors, LaCoste and Romberg Stabilized Platform Meter.

stant course and speed which affects meter performance, and (2) the determination of position and course and speed which affect the computation of the Eötvös correction. All systems are adversely affected by periodic variations in course due to wave action or to inexperienced helmsmen and by intentional course and speed changes; as much as 15 or 20 minutes of data may be lost after a major change. The solutions to these difficulties are at variance; wave action would require greater damping, while course and speed changes would require less damping.

An analysis of the Eötvös correction (fig. 15), which is due to the vertical component of the Coriolis acceleration, clearly indicates that either the speed with respect to the ground must be known to 0.15 knot and course to slightly better than 1 degree, or the east velocity must be known to 0.15 knot for a one-milligal uncertainty. To achieve this accuracy, positions obtained at 1-hour intervals must be known to ± 600 feet and then it must be assumed that course and speed remained constant during this interval. Greater accuracy is required for positions obtained over shorter time periods. Except for large gravity gradient regions, a position accuracy of ± 1/4 mile would be satisfactory, if not needed for ve-

$$EC = 7.503\ V \sin A \cos \phi + 0.00415\ V^2,$$

V = ship's ground speed, knots
A = course made good, clockwise from north
ϕ = latitude

FIGURE 15.—Eötvös correction.

locity determination. Therefore, where we are is of a great deal less significance than where we're going and how soon we'll get there.

Advances in inertial guidance systems hold great promise. Probably a combination of data obtained from an inertial system updated by satellite navigation is the immediate solution. Recently, on a west coast upper mantle project accomplished by the USC&GS ship *Pioneer*, satellite navigation resulted in a standard deviation of ± 0.5 knot, or ± 3.2 mgals in Eötvös correction, when r.p.m. and course were constant. These figures include variations in current but must be considered the minimum errors to be expected from satellite positions obtained at approximately 90-minute intervals. Slightly better results could be expected from more frequent satellite positions, if available, or from a system which would provide the navigational detail between satellite position fixes. On the same project a standard deviation of more than ± 1 knot was determined when speed and course changes occurred between satellite fixes resulting in a standard deviation of the order of ± 6 mgals in the Eötvös correction.

Realistically, then, stable table marine gravimetric systems under reasonable sea conditions, when properly tuned and handled, give values within a standard deviation of ± 3 mgals. With reliable navigation the standard deviation should range from ± 4.5 to ± 7 mgals. Of course, with some knowledge of the gravity field as that provided by a reconnaissance type underwater survey at 10-mile spacing, and with precision navigation as provided by near land-based electronic systems, this error can be reduced to the ± 1 or ± 2 mgal range. Possibly the same accuracy can be expected in open ocean surveys, if bottom gravity stations can be established and recovered and the Eötvös correction can be determined from more precise navigation data or from a locally established system.

Report on Prototype Gravity Measuring System

Constructed by Bell Aerosystems Company for U.S. Naval Oceanographic Office and U.S. Coast and Geodetic Survey

As early as 1963 research into advances in missile and inertial guidance technology indicated that commonly used components could be modified and used together to measure gravity. In March 1964 the U.S. Naval Oceanographic Office and U.S. Coast and Geodetic Survey jointly prepared performance specifications for an improved gravity measuring system and requested proposals for its construction. The response brought forth several new ideas for the measurement of gravity. The proposal of Bell Aerosystems Company was selected and a contract for construction of the system was signed June 16, 1965. Operational acceptance tests of the Bell Gravity Measuring System over the Gravity Equipment Evaluation Range off Wallops Island, by NAVOCEANO and the Coast Survey, were completed June 14, 1966. The system performed well within specifications under a wide variety of sea conditions and was accepted for operational use. This report describes the equipment and the test procedure.

THE SYSTEM

The Bell gravity measuring system contains three basic subsystems—the sensor, the stabilized platform, and the dynamic digital filter. Each subsystem is complete with individual power supplies and performance monitoring circuitry. This design provides maximum flexibility of component interchange and usage configuration.

The sensing element of the sensor subsystem, the Model VII accelerometer manufactured by Bell Aerosystems Company, has a long history of dependable usage in a variety of instrumentation. It is essentially a single-axis inverted pendulous force balance accelerometer. The proof mass, basically a coil, is electronically constrained for a mechanical null in a high-flux magnetic field. The current required for constrainment is proportional to the acceleration acting on the instrument. A high constrainment, 0.01 milliradians per G, is used to prevent the coupling of components of cross axis accelerations into the sensitive axis direction. This is a normal feature of inertial quality accelerometers; thus, in this type of instrument, no cross coupling computations are required. A precision bias is subtracted from the sensor output in an operational amplifier to provide the sensor with an operating range of 27,000 milligals. The analog signal output passes through a 30-second filter to remove high frequency noise and filtered signal passes through a precision analog to digital converter, which transforms the analog signal, the constrainment current, into a pulse rate proportional to gravity. The analog-to-digital converter in this case is a pulse rate generator developed for use in the digital velocity meters of inertial navigation systems.

The completed sensor subsystems demonstrated static accuracy of 0.1 milligal. This was verified in the laboratory by correlation with diurnal tidal effects.

Stabilization of the sensor subsystems is achieved by a two-gimbaled platform stabilized in the apparent vertical and provided with automatic compensation for the horizontal acceleration components coupled into sensing axis by tilts of the platform.

Economy and ease of maintenance of this technique were the criteria for its selection, and there is no degradation of data when compared to the precise Schuler-tuned system which maintains the absolute vertical.

This technique required only a one-percent stabilization system to provide one-milligal accuracy in the presence of 100-gal accelerations. Components for such a system are well within the state-of-the-art and it is therefore possible to effect replacement of major components with no adjustment required to maintain the system accuracy. The platform accelerometers are equivalent to the sensor and the gyros are manufactured by Reeves to specifications prepared by Bell.

The control panel for the platform contains meters and switching circuitry that provides the operator with a continuous monitor of the performance of all major components.

A dynamic digital filter with a smoothing time of 5 minutes was designed to separate the value of gravity from the vertical accelerations due to ship's motion. This filter with the 30-second filter provided in the operational amplifier of the sensor subsystem, provides an attenuation of 100,000:1 for noise having periods of up to 15 seconds. The digital output of the pulse rate generator is fed into the digital filter where the pulse count for each second is treated by the appropriate forcing function coefficient. Three hundred (300) weighted pulse counts (5 minutes) constitute a single observation.

The forcing function coefficients are entered into the digital filter by means of a recirculating punched mylar tape. The tape contains five sets of coefficients for the forcing function appropriately staggered to allow an output rate of one value per minute. The forcing function used is $1 - \cos x$, however, this may be changed at any time by replacing the punched tape with any other prepared function.

Base gravity is entered into the filter as offset and with the scale factor for the sensor in use, the filtered pulse rate is reduced to gravity. The filter produces a hard-copy printout of one gravity value per minute for visual control and a magnetic tape of the same data along with date and time. There is also provision for manual input to the magnetic tape.

The objectives of the system were to obtain accurate gravity data with a high degree of reliability; a minimum of operator care, maintenance, and data handling, and to extend the limits of operational use. Laboratory performance indicated that these objectives had been obtained through the design of a meter to operate under dynamic conditions in a specific environment.

Accurate data has been measured by the sensor and stabilized platform under noise conditions much greater than specified. Data handling was minimized in that the output of the meter requires only the addition of a linear drift correction and the Eötvös correction and this can be done directly with the magnetic tape recording system. Minimum care and maintenance and high reliability appear to have been achieved through the incorporation of conservative component requirements with the use of highly reliable components throughout the system. Since the system was designed to dynamic specifications, each component value could be calculated and a reliability factor added. Modular construction, built-in test and monitoring features facilitate trouble location and repair. Failsafe and system-disable checks prevent disasters.

Data reliability is improved through the use of performance monitors which allow the operator to rapidly determine the status of each subsystem by providing GO-NO-GO displays of critical elements. Self-test features have been built into each subsystem to provide a second level of fault-finding capability. Meters on the panels provide a continuous monitor of critical signals within the subsystem. If an acceptable signal level is not maintained, various elements of the subsystem are disabled. The subsystem is then automatically switched into a self-protecting stand-by mode until the malfunction is acknowledged by the operator.

No component failure was reported by the manufacturer during construction and testing in the laboratory. At the end of the test program, the system was delivered for operational test at sea.

TEST PROCEDURE

Performance specifications for the operational trials at sea as follows.

Accuracy:

Static: 0.1 milligal

Drift: Predictable within 1 mgal per month

Dynamic: For acceleration up to 100,000 milligals peak to peak; 1.0 milligal for motion periods up to 15 secs, 2.0 milligals for motion periods greater than 15 secs

Environmental conditions:

Temperature: 60° to 110°F

Humidity: 90 percent

Output: One percent per minute on paper tape with a resolution of 0.1 milligal.

The operational acceptance tests of the Bell Gravity Measuring System were conducted on board the USNS *Sgt. Curtis F. Shoup* over the Gravity Equipment Evaluation Range located off Wallops Island, Va. The instrument was installed in the survey compartment on the second deck; approximately over the rotation center of the pitch axes, and 10 feet off the center line at approximately the level of the rotation center of the roll axis.

The specifications of the ship are: 338-foot length, 50-foot beam, 21-foot draft, about 3,000 tons displacement unloaded, and top speed 11.5 knots. Motion characteristics of the vessel are very suitable for gravity operations. The ship has been used for gravity surveys since 1962.

A LaCoste and Romberg gimbaled sea meter was installed in the compartment with the Bell Meter. This meter, selected from NAVOCEANO survey equipment because of a favorable combination of performance, sensor, and electronics, was used to monitor the functioning of the Bell instrument during the test.

A test survey pattern was run over the Evaluation Range. A survey line of about 120 miles length also was run to the east of the range to check meter performance over a large gravity change and to obtain some data in actual deep-water conditions. Since precise data to check the survey was not available for comparison purposes, the Bell meter performance was inferred from comparison with the tested LaCoste and Romberg instrument.

Precision positioning and navigation over the range were obtained from a permanent Raydist network established in the area. This network provides the range with position accuracies that are better than 100 feet. The precision electronic system was supplemented by gyrocompass, speed indicator, DATEX recorder for the Raydist receiver, Sperry analog recorder for the gyrocompass, and auto pilot steering.

A survey team of personnel from Bell Aerosystems Company, Coast and Geodetic Survey, and Naval Oceanographic Office conducted the tests. Continuous watches were maintained for the gravity and navigation equipment. Data were reduced for preliminary evaluation during the survey.

Test conditions were perfect in that the basic cartwheel pattern over the range was begun on June 7 in calm weather (sea state 2). This condition prevailed until noon on June 11. June 11 and 12 operations were conducted in winds up to 45 knots and sea state of 4 to 5. The conditions moderated on June 13 and the weather was calm until the end of the test period on June 14. The environmental conditions encountered during the test period are summarized in table 1. The wind direction and speed and sea and swell conditions shown in the table were selected from estimates by various members of the test team, including the greater estimating experience of the mate on watch. The horizontal and vertical acceleration data presented in the table were derived from visual monitoring of the acceleration indicators on the Bell Meter and the analog output records of the LaCoste and Romberg meter beam and horizontal accelerometers. The most adverse environmental condition was recorded on 11 June. Average horizontal and vertical accelerations were 88 gals and 80 gals, respectively, with peaks of 250 gals and 275 gals. The worst comparison with range data, a RMS discrepancy of approximately 3 milligals, including position and navigation error, was obtained under these conditions.

By contractural agreement, a maximum of two milligals discrepancy was permitted as error resulting from uncertainties of position and navigation. Since the meter was developed under a fixed-price contract with acceptance contingent on performance within the operational specifications, every precaution was taken to maintain the integrity of the navigation data.

The Raydist output was printed automatically by the DATEX recorder at one-minute time intervals until June 12th when a malfunction of the recorder necessitated manual recording of the Raydist dials. This was done at 5-minute intervals for the remainder of the test period. The Raydist data was plotted at 5-minute intervals for the entire test period. At the end of each line of the test pattern a navigation overlay was prepared. This was immediately evaluated by the data-reduction team. Discrepancies were quickly noted and the ship returned to the Chesapeake Bay light tower for recalibration of the navigation system. Recalibration was required five times during the survey. In these cases, all positions adopted as final were adjusted prior to recalibration and the adjustment was confirmed by recalibration. Nevertheless, three lines of data were rejected completely because no satisfactory adjustment of navigation was possible. The gyrocompass and analog course recorder were in operation for the total test period and, except for the period of rough weather from June 11 to June 13, the ship's course was maintained by auto pilot.

The meter was installed on board the ship and a tie to the local gravity base station was completed by June 6. The gravity value offset was entered into the digital filter and the filtering program was activated. A check of the printed output of the meter before the start of the survey on June 7 revealed that the meter output had changed in exact magnitude with the local tide.

After calibration of the Raydist system on June 7, the survey over the test pattern commenced. The planned survey included 16 lines with data obtained on reciprocal courses on each line or a total of thirty-two data lines. Since constant speed and course was considered more important than planned track, deviation from the track was not corrected by course change, thus, the line distribution of the actual survey had a more or less random appearance. Loss of the lane count of the navigation system also contributed to scattered appearance of the surveyed lines. Data were obtained on thirty-one lines but three lines were rejected because of inadequate navigation.

Much of the data reduction normally associated with gravity surveying is accomplished automat-

Table 1.—Environmental Conditions and Effects During Test Period

Line No.	Time	Course	Steering	Wind direction and speed	Sea state	Waves dir.-hgt.	Swell dir.-hgt.	Average vertical	Average horizontal	Surges vertical	Surges horizontal	Line RMS
1	2300-0040	180	Auto Pilot	200-12	2	200-3	200-5	16K	12K			0.19
2	0120-0240	022	..do.....	200-12	2	200-3	200-5	16K	12K			0.22
3	0315-0450	235	..do.....	200-12	2	200-3	200-5	30K	28K			0.91
4	0515-0700	068	..do.....	200-12	2	200-3	200-5	30K	28K			0.34
5	0730-0910	270	..do.....	200-12	2	200-3	200-5	16K	10K			0.21
6	0945-1130	112	..do.....	200-16	2	190-3	200-5	20K	12K			1.06
7	1200-1340	315	..do.....	200-16	2	190-3	200-5	10K	6K			0.21
8	1445-1640	158	..do.....	190-16	2	190-3	200-5	12K	10K			0.84
9	0040-0230	202	..do.....	200-12	2	200-3	200-5	16K	12K			0.61
10	0310-0445	045	..do.....	200-12	2	200-3	200-5	13K	11K			0.74
11	0535-0715	135	..do.....	200-12	2	200-3	200-5	18K	20K			1.19
12	0755-0940	090	..do.....	200-12	2	200-3	200-5	18K	20K			0.39
13	1010-1145	292	..do.....	200-16	2	190-3	200-5	10K	11K			0.66
14	1230-1400	136	..do.....	190-16	2	190-3	200-5	6K	10K			0.23
15	1430-1600	338	..do.....	190-16	2	190-3	200-4	6K	2K			0.49
16	1625-1825	180	..do.....	185-17	2	185-3	180-5	8K	10K			0.96
17	1105-1430	060	Helmsman	025-25	4	025-6	025-12	50K	32K	70-75K	36-40K	2.46
18	1525-1655	270	..do.....	030-29	4	030-6	040-14	38K	65K	50-60K	100-140K	1.42
19	1815-2155	112	..do.....	045-35	4	045-7	045-14	80K	88K	150-275K	120-250K	2.97
20	0310-0500	227	..do.....	045-40	4	045-7	045-14	32K	29K	40K	60K	1.10
21	1245-1815	030	..do.....	010-45	5	010-9	025-20	60K	78K	80-150K	100-160K	1.82
22	0830-1030	090	..do.....	310-18	4	310-6	045-10	50K	40K	75-140K	50K	1.21
23	1100-1245	293	Auto Pilot	310-15	3	310-5	040-8	50K	50K	75-150K	75K	1.43
24	1320-1450	107	..do.....	290-15	2	290-3	045-8	50K	40K	75-150K	50K	0.93
25	1520-1700	315	..do.....	290-12	2	290-2	045-8	40K	40K	75-100K	50K	0.62
26	1720-1900	130	..do.....	290-12	2	290-2	045-8	50K	50K	90K	50K	0.54
27	1945-2130	338	..do.....	215-8	2	215-2	040-6	40K	40K	100K	40K	0.67
28	0230-0350	202	..do.....	220-8	2	222-2	040-6	6K	6K			0.50

ically in the digital filter of the Bell Meter. The base value reduced to shipboard value is entered into the digital filter as an "offset" where it is combined with the sensor scale factor and the filtered output of the sensor. The output of the digital filter is a gravity value per minute reduced to the base value (table 2). This value is printed for visual monitoring as shown in table 2 and entered on magnetic tape for machine processing. Although it is possible to vary the vertical motion filtering technique by reprogramming the digital filter, all data during this test were obtained over 5-minute intervals using the coefficients of 1 - cos x as the vertical noise filter.

The preliminary data reduction demonstrated the sensitivity of the meter to the Eötvös effect. The course and speed corrections for the final test data smooth plotted by entire line or by short line segments when the navigation plot and gyro compass recorder indicated the necessity.

Meter drift, predicted from laboratory checks to be about 3 milligals, was measured at 2.7 milligals. This was applied to the observed data during the final computations.

Table 2.—Sample of Digital Filter Output

Time	Gravity base value	Time	Gravity base value
0537	9799474	0510	9799697
0536	9799458	0509	9799706
0535	9799447	0508	9799717
0534	9799436	0507	9799730
0533	9799431	0506	9799743
0532	9799430	0505	9799753
0531	9799430	0504	9799762
0530	9799425	0503	9799771
0529	9799417	0502	9799777
0528	9799404	0501	9799778
0527	9799391	0500	9799778
0526	9799377	0459	9799784
0525	9799361	0458	9799806
0524	9799349	0457	9799834
0523	9799346	0456	9799851
0522	9799343	0455	9799860
0521	9799354	0454	9799870
0520	9799424	0453	9799880
0519	9799532	0452	9799889
0518	9799606	0451	9799897
0517	9799624	0450	9799905
0516	9799629	0449	9799914
0515	9799637	0448	9799925
0514	9799649	0447	9799936
0513	9799665	0446	9799943
0512	9799681	0445	9799947
0511	9799690	0444	9799955

The data obtained were tabulated by line and summarized in an appendix to this report (not included in this publication). By comparison with the range gravity values, nineteen of the twenty-eight accepted data lines had Root Mean Square discrepancies less than 1 milligal, seven of less than 2 milligals, and two of less than 3 milligals. The RMS-comparison difference for the entire test period was less than 1.5 milligals.

The distribution of comparison differences by discrete point values for each five minutes of accepted track is given below.

373 observations compared between 0-1 milligal
111 observations compared between 1 and 2 milligals
20 observations compared between 2 and 3 milligals
16 observations compared between 3 and 4 milligals
11 observations compared between 4 and 5 milligals
4 observations compared between 5 and 6 milligals
2 observations compared between 6 and 7 milligals

The error contribution of position and navigation correction is not separated in the comparison differences presented in the data summary; however, since standard procedures were used throughout the test, the results show that the meter performed well within the accuracies specified. Component failures did not occur during the test. Although it is impossible to conclude average component life from this short period, the design and engineering of the meter impart a measure of confidence to the overall reliability and dependability. The meter has been accepted and is scheduled for use during operational surveys in the very near future.

Inasmuch as the test was conducted specifically for the evaluation of a new meter with respect to a performance specification, little attention has been devoted to reviewing the unique features of the instrument. A cooperative effort by NAVOCEANO and the Coast and Geodetic Survey will be directed toward complete analysis of the data and a review of the unique features. A suggested plan for this analysis includes optimizing the filtering of the data through the digital filter and a thorough analysis of the components of velocity, which, in the actual environment, produce changes in the gravity vector magnitudes.

Although about 70 percent of the data obtained during the test compared with range values better than 1.0 milligal, it is not certain that the best possible accuracy has been obtained. Standard techniques were used throughout but the meter is not designed to the standard techniques of grav-

imetry. Much of the design and engineering for this instrument was based on research that has been directed toward solution of the precision navigation problem through inertial instrumentation and its application to the problem of measuring gravity on a moving platform.

It is interesting to note that an Inertial Navigation System, operating on a local vertical coordinate system, senses a component of acceleration proportional to curvature of the potential surface. This component, added to the true accelerations and integrated, appears in the velocity and position output of the system. The gravimeter, operating on the same platform, senses the magnitude changes of a gravity vector generated by the addition of the magnitude of the local gravity vector and a component of gravity proportional to the true velocity of the platform with respect to the rotation of the earth. It then follows that a perfect gravity meter operated in conjunction with a perfect local vertical inertial system would both be limited in their respective functions by the same term, the velocity generated by the inertial system and applied to the gravity measurement.

While it is true that presently there is not enough available data to pursue this idea to a conclusion, an analysis of available data may provide an insight to what will be possible in the very near future.

A New Ocean-Floor Gravimeter Utilizing a Vibrating String Accelerometer

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APPLICATIONS

Surface-ship gravimeters have been improved to the point where sea-surface accelerations are no longer the limiting factor. Aside from the error in the Eötvös correction, measurements to the order of 0.1 mgal may soon be possible. With Eötvös correction errors included, accuracy may deteriorate to ±10 mgal. However, large features such as trenches and seamounts may be investigated satisfactorily with this accuracy and, considering the present gravity coverage of the oceans, geodetic requirements are moderately well satisfied. One might therefore question the usefulness of the bottom gravimeter.

The answer lies in the differences between surface and bottom gravimetry. Each method has its strong points, although it must be admitted, the balance generally weighs in favor of surface gravimetry. Use of the surface gravimeter is adequately described in the literature of the past few years. Much less is written about bottom gravimetry. I should like here to cite instances where the bottom gravimeter has proven useful and where it might find future applicability.

(1) The instrument precision of the bottom gravimeter is essentially the same as that of the land gravimeter [Beyer et al., 1966]. Geophysical investigations of small structures, or of subtle density changes, require high precision. For this reason, oil exploration groups were the first to construct and extensively use bottom gravimeters. Their investigations were naturally limited to the continental shelf or depths of about 200 meters.

(2) More recently, the prospecting-type gravimeter has been modified for use at greater depths as interest in subtle density variations in other than shelf areas has increased. A modified LaCoste underwater gravimeter has been used at a maximum depth of 904 meters [Beyer et al., 1966].

(3) Bottom gravimeters are stationary and not subject to Eötvös corrections. For this reason, they are used to establish gravity ranges in shelf areas to test and evaluate surface-ship gravimeters [Fanning and Garoutte, 1962].

These applications have been easily achieved because in shallow water the bottom gravimeter has few operational difficulties. Other applications will require greater effort.

Gravity data, to be useful, must be corrected to a reference elevation. In deep water this can require measurement of instrument depth with a precision of the order ±0.01 percent. Commercially available deep-water pressure transducers, at present, are not capable of such precision. However, if absolute depth is not required, as in geophysical investigations of small structures, areas of gentle topography can be surveyed by using a ship's precision depth recorder to indicate small, relative, depth changes.

To date, bottom gravimeters have been remotely operated on multiconductor cable. In this mode of operation, on-station time consists mainly of the time required to lower and raise the device. This amounts to about one hour for each kilometer of depth. In addition, holding an acceleration-sensitive instrument quiet at the end of a 5-km length of cable in moving water is difficult and impractical, if not impossible. If these problems

can be solved, the 92 percent of the ocean floor deeper than 200 meters will be opened for investigation. The following applications may then be possible:

(1) Gravity base stations and ranges could be established in the deep ocean to aid surface surveys. These stations would be valuable for detecting gravimeter tares or for recalibrating gravimeters with large drift rates.

(2) It is expected that there are large areas of the ocean where free-air gravity anomalies change very slowly. A coarse grid of accurate bottom gravity measurements in these areas would suffice for geodetic purposes.

(3) The vertical gradient of gravity at the sea surface is a measure of the local mean curvature of the geoid [Bodemüller, 1963]. However, two complications reduce the applicability of simple gradient measurements using surface and bottom data. First, the gradient derived from the surface and bottom measurements can differ from the gradient at the sea surface due to the presence of disturbing masses at the bottom. That is, the vertical gradient may not be constant with elevation but may vary considerably near local masses that give rise to anomalies. In some areas this effect is small. In other areas a topographic reduction of the bottom measurement is sufficient. Second, the vertical gradient indicates the mean curvature, but not the variation of curvature with azimuth. Additional surface gravity measurements are required for the resolution of the azimuthal variation.

In spite of these difficulties, surface- and bottom-derived vertical gradients serve as valuable checks on curvatures derived from surface measurements alone. This type of measurement is especially suited for the proposed geodetic base stations. By using acoustic transponders at these stations, relative location and vertical separation of surface and bottom gravimeters can be precisely determined. An accuracy of 0.1 mgal at these locations is conceivable for both surface and bottom measurements.

(4) Accuracies of ±0.1 mgal in gravity measurements can make possible a new determination of the gravitational constant. Suppose a base station were located in an area where the established variability of the bottom gravity anomalies was of the order ±0.1 mgal. Suppose further that surface gravity were sufficiently well measured to 10^{-12} cm^{-1}. In other words, suppose that the measured vertical gradient could be corrected with a precision of about 0.5 Eötvös to be a measure only of the elevation and Bouguer effects. If technologically feasible measurement accuracies of ±0.003 percent for mean sea-water density, ±.01 percent for gravimeter separation, and ±0.1 mgal for gravimeter accuracy on a stationary ship are used, the maximum error in the gravitational constant would be about .06 percent or 1/1600--compared to the present uncertainty of 1/500.

THE INSTRUMENT

A fully automatic bottom gravimeter has been built that can be operated in two different modes: (1) free-fall, and (2) automatic on a nonconducting cable. Slight modification would allow a third mode--remote readout on single conductor cable. With these capabilities, it is hoped that the difficulties and possibilities of deep-sea bottom gravimetry may be evaluated.

In choosing a sensor, commercial land gravimeters were, of course, considered. However, W. S. von Arx of Massachusetts Institute of Technology and Woods Hole Oceanographic Institution suggested that inertial guidance accelerometers also be considered. Accelerometers, in general, have high drift rates, but their modes of operation are a decided advantage. Since accelerometers are constantly being improved, it was decided to live with a marginal stability. We were very fortunate in obtaining an American Bosch Arma Lot D vibrating string accelerometer from the U.S. Air Force.

The principle of the vibrating string has been described several times in recent geophysical literature [Goodell and Faye, 1964; Howell et al., 1966]. As a simple approximation, the resonant frequency of a vertical string with attached mass (fig. 1) is:

$$f = 1/2L \sqrt{(M_g + T_o)/\rho}$$

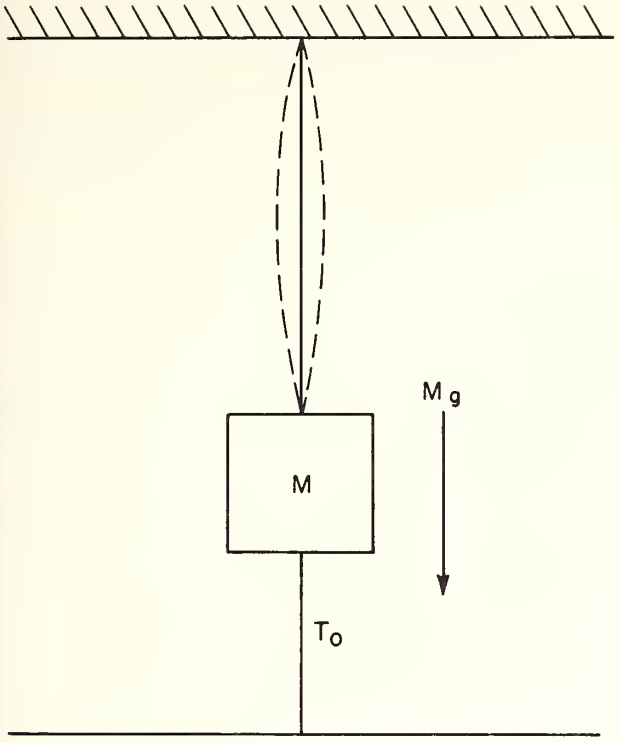
where: L = string length
M = attached mass
g = acceleration of gravity
ρ = string mass per unit length
T_o = stress due to clamping lower end of string

The frequency-gravity relationship may be expressed as a MacLaurin's series:

$$f = K_o + K_1 g + K_2 g^2 + \ldots$$

When placed in the field of a permanent magnet, the vibrating string is subjected to an induced voltage which can be amplified and fed back to maintain oscillation. Previously, all vibrating string gravimeters have been of the single string design.

The Arma accelerometer uses two oppositely oriented strings as in figure 2. With an increase in gravity the tension and frequency of string 1 increase, but the tension and frequency of string



$$f = \tfrac{1}{2} L \sqrt{\frac{Mg + T_o}{\rho}}$$

$$= K_0 + K_1 g + K_2 g^2 + \cdots$$

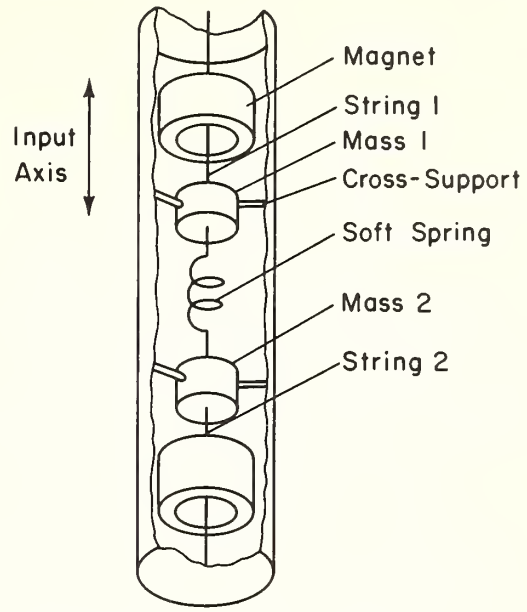
FIGURE 1.—Simple prestressed vibrating string with attached mass.

2 decrease. The difference frequency, expressed as a MacLaurin's series, is

$$F = (K_{10} - K_{20}) + (K_{11} + K_{21})g + (K_{12} - K_{22})g^2 + \ldots$$

If the strings were identical, all even order terms would be zero. Most of the double string instability occurs in the bias term $(K_{10} - K_{20})$. However, inverting the accelerometer 180° and adding the two resulting difference frequencies eliminates the bias term and all other even-order terms. The remaining drift (fig. 3) is greatly reduced and quite linear with time so that interpolation between calibrations is possible.

A cross section of the gravimeter is shown in fig. 4. The accelerometer is mounted in a plexiglas cylinder which floats vertically within a glycerine filled sphere (C). The cavity between sphere (C) and polyurethane foam sphere (D) is filled with demineralized ice and water, holding the accelerometer temperature at 0° C. Accelerometer electronics and a silver cadmium battery power supply are contained within the freely floating cylinder. Accelerometer vertical is achieved to ± 1' with a cylinder pendulosity supplied by mercury in cavity (A1). Automatic



$$f_1 = K_{01} + K_{11} g + K_{21} g^2 + K_{31} g^3 + \cdots$$

$$f_2 = K_{02} - K_{12} g + K_{22} g^2 - K_{32} g^3 + \cdots$$

$$\Delta f_{+g} = (K_{01} - K_{02}) + (K_{11} + K_{12}) g + (K_{21} - K_{22}) g^2 + \cdots$$

$$\Delta f_{-g} = (K_{02} - K_{01}) + (K_{12} + K_{11}) g + (K_{22} - K_{21}) g^2 + \cdots$$

$$\Delta f_{+g} + \Delta f_{-g} = 0 + 2(K_{11} + K_{12}) g + 0 + \cdots$$

FIGURE 2.—The American Bosch Arma vibrating string accelerometer (VSA).

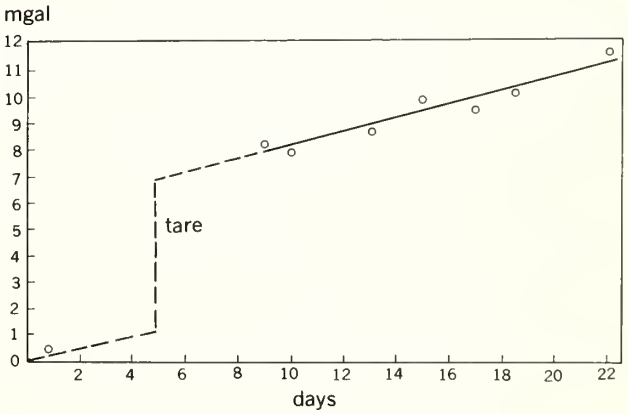


FIGURE 3.—Typical VSA scale factor drift showing interpolation.

inversion of the accelerometer results from the rotation of the outer sphere (D) through 180°. The cylinder is viscously dragged through nearly 180° and the mercury in cavity A1 flows through tubes to cavity A2, causing the cylinder to seek the opposite vertical to ± 1'.

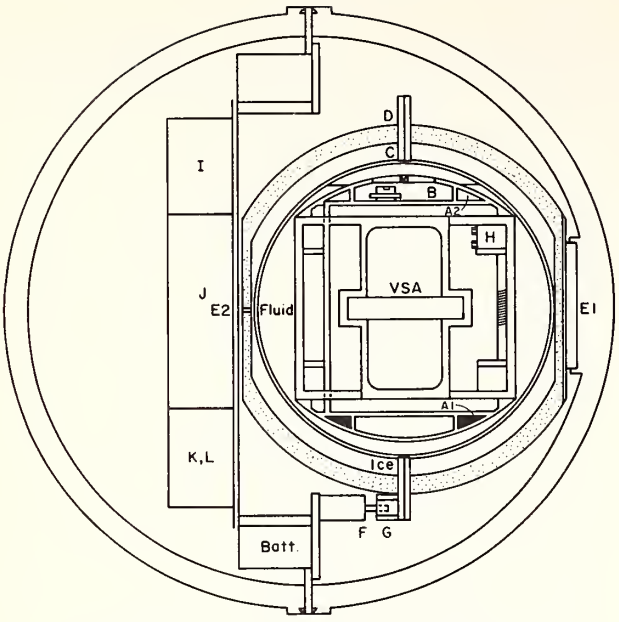


FIGURE 4.—Gravimeter cross sectional view.

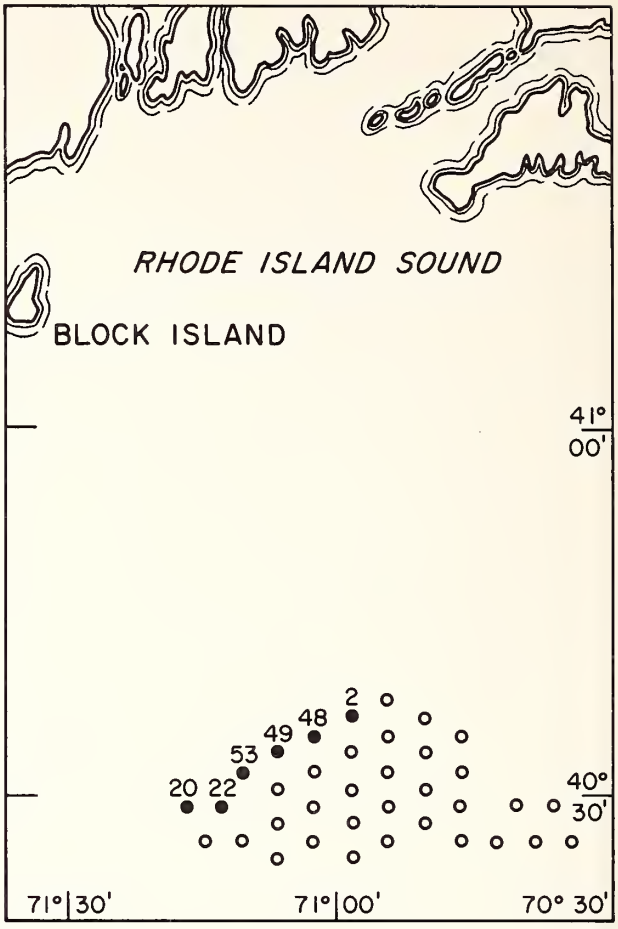
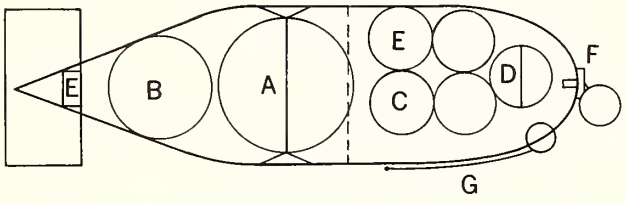


FIGURE 6.—Rhode Island Sound area gravity meter operational check range showing stations reoccupied.



A 19″ i.d. instrument sphere
B 16″ glass sphere
C 10″ glass spheres
D 9″ Benthos sphere, radio, strobe
E 9″ Benthos sphere, Webb pinger
F Mg weight release
G C. B. radio antenna

FIGURE 5.—Free-fall vehicle—a modified free oceanographic instrument float.

The accelerometer frequency signal is transmitted by AM radio to receiver (I) where it is demodulated. The frequency (period) is measured by counter (K) and the binary information is recorded on film. The number of automatic measurements is limited by the power spring (E1) which supplies the inverting torque. A sequence timer controls the measurement operations plus the interval until first measurement and the number of measurements desired.

The instrument can be lowered on a cable to its design depth of 27,000 feet. In addition, a free-fall to the same depth is achieved with the fibreglas vehicle shown in figure 5. Buoyancy is provided by glass spheres. The vehicle descends nose first, weighted by an anchor attached with a van Dorn magnesium weight release. The vehicle is balanced to lie on its side on the bottom during measurements. Upon release of the anchor the vehicle ascends nose first. Original plans incorporated a Bissett-Berman vibrating string pressure transducer. With the unavailability of this device, the depth of the instrument is obtained with a standard, reversing, protected and unprotected thermometer pair attached to the vehicle. If the bottom is smooth, a ship's precision depth recorder can be used. Vehicle hor-

izontal coordinates are obtained by acoustic range-rate measurements on a 4-kHz precision time base "pinger" located in the vehicle tail. Recovery is aided by the vehicle's orange color, the 1-watt citizens' band transmitter, and the 1-watt-second strobe flash.

The instrument has been given one field test to date. Six stations of the Rhode Island Sound Area Gravity Range [Fanning and Garoutte, 1962] (fig. 6) were reoccupied in April 1966 with the instrument on a cable. Five measurements were successful. The sixth attempt failed, apparently because of mishandling and failure of the vehicle to invert. Three gravity measurements were made at each station in order to evaluate repeatability. The rms difference between the range values and the measured values was 0.43 mgal, an unknown portion of which was due to uncertainties in depth and location. The mean difference between range and measured values was +0.14 mgal.

We hope that further use of the instrument in its different modes in deep water will provide valuable information on the difficulties and possibilities of deep bottom gravimetry.

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Ocean Gravity Surveys With Airborne Systems

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I

The knowledge of the earth's external gravity field is an essential requirement for precise determination of gravity dependent earth parameters and for the successful utilization of gravity data in physical geodesy. In addition, inertial navigation instruments utilized for ships, aircraft, and space vehicles cannot perform with the desired accuracies without the knowledge of the variation of the gravity field. Over accessible land areas terrestrial gravimetry provides the measurements with adequate accuracy, however, this method is economically feasible only over well developed areas. In inaccessible land areas and over the oceans, which constitute more than two-thirds of the earth's surface, new methods and instruments are required for the accomplishment of gravity measurements.

Is there a requirement for gravity measurements over oceans and inaccessible land areas? The answer is a firm yes, provided we intend to improve essential earth constants by means of physical geodesy and we want to utilize the achievements of inertial instrumentation technology for accurate navigation. Theoretically, there are two possible ways to obtain the global external gravity field of the earth: First, by direct surface and aerial gravity surveys to fill in the gaps existing over unsurveyed areas; and second, by utilization of the external gravity field described by spherical harmonic coefficients derived from satellite tracking data. Studies conducted on this subject indicate that harmonic coefficients, derived from satellite data are both unreliable and inadequate to satisfy the requirements of scientific geodesy and navigation without the support of direct global measurements. The combination of the two methods would be the best approach for a reliable solution of all problems dependent on the gravity field of the earth. The minimum requirement for direct measurements would be a global coverage in form of mean anomalies for 5° x 5° blocks with ±5- to ±10-mgal accuracy. The mean values can be derived most economically from two or three east-west aerial profiles across each block.

II

In 1958 AFCRL conducted the first experiments of aerial gravimetry with a modified LaCoste and Romberg sea gravimeter in a KC-135 aircraft. Later, the Askania-Graf sea gravimeter was also included in the tests. These early experiments proved that aerial gravimetry is feasible and that satisfactory accuracies can be achieved provided navigation errors can be reduced below certain limits. Additional test flights and experiments were carried out by AFCRL in 1960 and 1962. The feasibility of aerial gravimetry was confirmed by these experiments and it was also concluded that a great number of problems must be resolved before an operational airborne gravity measuring system could be achieved. Fairchild (FLAGS) Corporation flew a triangular pattern at 12,000 ft using a LaCoste and Romberg instrument and a B-57 aircraft in 1961. This test also indicated the feasibility of aerial gravimetry. In January 1965 AFCRL was provided with a KC-135 aircraft and the means required for the intensification of research and tests in aerial gravimetry. The goals of the new effort were: To select and designate components of a complete airborne gravity measuring system which would satisfy minimum requirements; to derive data reduction methods, including computer programs; and to resolve the downward continuation problem of gravity for the purpose of obtaining useful ground or sea-level values from high-altitude aerial profiles.

Gravity measurements obtained by airborne sensors, like any other moving gravity measuring technique, are affected by the Eötvös effect. This is composed from the vertical components of the Coriolis and centripetal accelerations resulting from the motion of the aircraft. This effect, which is several thousands milligals, can be com-

puted from the aircraft's navigation data. If the navigation data are not accurate enough the Eötvös correction will be in error. The critical navigation data are ground speed (velocity error) for east-west flights and azimuth for north-south flights.

A one-knot error in the ground speed for east flights at 400 knots produces errors in the Eötvös correction ranging from 10.8 mgal at the Equator to 4.6 mgal at latitude of 80°. For west flights the same velocity error will affect the Eötvös correction by 4.2 mgal at the Equator and by 2.0 mgal at latitude 80°.

The effects of azimuth errors are linear functions of aircraft velocity. An error of 0.1 degree in azimuth for north-south flights at 400 knots will result in Eötvös correction errors ranging from 5.2 mgal at the Equator to 0.9 mgal at latitude 80°.

Geographic latitude and earth radius errors contribute to the Eötvös correction errors but the combined effect is less than one mgal under current conditions. Figure 1 shows the errors in the Eötvös correction at various latitudes and azimuths assuming that (a) the ground speed is accurate to ±0.5 knot; (b) the azimuth error is ±0.1 degree; and (c) the latitude error is ±1.5 minutes of arc.

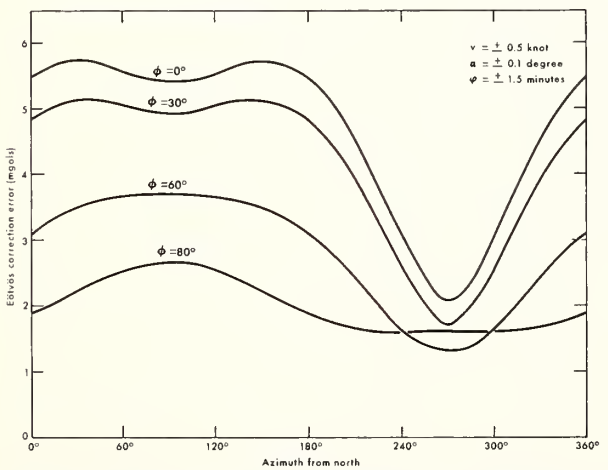

FIGURE 1.—Total Eötvös correction error at selected latitudes (Φ) and azimuths—assuming errors within limits indicated for ground speed (v), azimuth (α), and latitude (φ).

In addition to the Eötvös correction error, errors in the verticality of the stabilized platform, vertical accelerations of the aircraft, and errors in the elevation (flight altitude) of the aircraft are the major error sources in aerial gravimetry. Any one of these errors could exceed the allowed maximum for the combined total error under certain conditions, therefore, the greatest care is necessary in the selection of instruments, operation and data reduction to achieve acceptable results.

III

The KC-135 aircraft equipped with an APN-99 Doppler radar navigation system was gradually instrumented and modified to include the following gravity sensors and auxiliary instruments.

1. LaCoste and Romberg modified sea gravity meter with new solid state electronics, mounted on an ART-57 stable platform.
2. Askania-Graf modified sea gravity meter with new solid state electronics, mounted on an ART-25 platform.
3. Worden-quartz digital aerial gravity meter by Texas Instruments, Inc., mounted on an ART-57 platform.
4. ARP-5 airborne profile recorder with spotting camera.
5. Photo panel to record data from aircraft navigation system.
6. Analog-to-digital converter and magnetic tape recorder for recording gravimeter, APR-5 and navigation data.
7. MD-1 astrotracker for improved heading.
8. An accelerometer system mounted on the ART-57 platform of the LaCoste and Romberg instrument to record horizontal accelerations.

With the above described instruments a total of 450 measuring hours were flown between January '65 and May '66. From these, 364 hours flight time were satisfactory for data reduction and about 90 hours were rejected (prior to the data reduction) due to turbulence, instrument failures, and auto-pilot malfunctions. The flights were accomplished over three areas.

(1) Edwards AFB Test Range in California where the performance of the navigation system has been periodically checked by flights over the tracking range.

(2) South-Central U.S. Test Area covering an area of 6° in latitude and 7° in longitude. The existing ground gravity coverage of the area permitted the computation of profiles at aircraft altitudes with ±1 mgal accuracy. These "uplifted" profiles were used to evaluate the profiles measured by the airborne instruments. The area was covered in a grid pattern with profiles of 30 minutes spacing in east-west and north-south directions. All profiles were flown in both directions and the area is covered at 25,000 and 30,000 ft altitudes.

(3) North-Central U.S. Test Area which is 17° long in longitude and 3° wide in latitude. This area permits long profiles (800 miles). In contrast to the smoothness of the gravity field in the southern area, the gravity anomalies change more rapidly and attain much larger values than those in the south. This area was covered only by flights at 25,000 ft altitude with east-west profiles at 30-minute intervals and north-south lines with 1° spacing.

IV

The reduction of the collected data is in progress at the present time. The only measurements reduced are the east-west profiles over the South-Central test area. The preliminary evaluation of the reduced measurements show the following results.

1. *Mean Anomalies for* 5° *x* 5° *Blocks.* The error of the mean anomaly of an area is composed from the representation error of the number of profiles available for the computation of the mean value and from the measurement errors. Since the statistical representation error for one central profile in a 5° x 5° square is 13.4 mgal, a minimum of two profiles symmetrically located inside the blocks is required to meet the desired 5- to 10-mgal accuracy. Four pairs of symmetrically located profiles were found within the 5° x 5° block of the South-Central test area. Three pairs were observed with the LaCoste and Romberg gravimeter; they include one east and one west line each. The fourth pair was observed with both the LaCoste and Romberg and the Askania-Graf instruments. (The Askania gravimeter can measure, at the present time, only in the west direction because of its short range for airborne use).

One mean anomaly value was computed from each profile pair selected to represent the mean anomaly of the block. The mean also was computed from all available ground survey data and utilized as standard. From ground data the "uplifted" profiles, corresponding to the aerial profiles, were derived. From each corresponding pair the mean value of the block was computed (control profile pairs). From the comparison of these values the actual representation error, the actual total error, and the measurement error were obtained for each observed pair. The figures are shown in table 1. It can be seen that the mean of the LaCoste and Romberg actual total errors for this particular block is 7.1 mgal and 2.1 mgal is the actual total error of the mean value derived from one pair of *west* profiles measured by the Askania sensor.

The representation error termed as "actual" is valid only for this particular block and it is relatively small due to the smoothness of the gravity field in this area. If we use the statistical representation error determined from a statistical analysis of all existing gravity data, then for a 5° x 5° block, represented by two symmetrical profiles, the representation error will be ±6.4 mgal. Combining this with the standard measurement errors the total standard error for an average 5° x 5° block is obtained (line 11 of table 1).

The measurement errors were also derived from all available profiles in the test area. For the LaCoste and Romberg gravimeter 55 east-west pair combinations were available (one east and one west line in each pair). For the Askania gravimeter 36 pairs of west profiles were used. The differences between the measured and the "uplifted" control profiles were used for the computation of the standard errors which are ±7.4 mgal for the LaCoste and Romberg and ±4.2 mgal for the Askania-Graf gravimeter. Combining these standard errors with the statistical representation errors for two symmetrical profiles we obtain ±9.8 mgal standard total error for the LaCoste and Romberg and ±7.7 mgal for the Askania instrument.

Table 1.

(1)	Gravity meter	L-R	L-R	L-R	L-R	A-G
(2)	Flightline pair	35.5°E/39.5°W	38.5°E/36.5°W	37°E/38°W	39°W/36.5°W	
(3)	Mean anomaly 5° x 5° square (standard)	-5.7				
(4)	Mean anomaly (control profile pair)	-1.2	-5.6	-5.1	-7.8	-7.8
(5)	Actual representation error (4)-(3)	+4.5	+0.1	+0.6	-2.1	-2.1
(6)	Mean anomaly (observed profile pair)	+8.2	-10.7	-0.6	-10.0	-7.8
(7)	Actual total error (3)-(6)	-13.9	±5.0	-5.1	+4.3	+2.1
(8)	Measurement error (4)-(6)	-9.4	±4.1	-4.5	+2.2	0
(9)	Mean of L-R actual total errors	7.1				
(10)	Statistical representation error	±6.4				
(11)	Total error for 5° x 5° square	±11.0				±6.4

The Worden airborne gravimeter showed large systematic and random discrepancies with respect to the control data and to the values measured by the other two instruments. The average discrepancy was about 50 mgal. The electronics and the sensor of this system require additional studies before final conclusions can be made.

2. *Mean Anomalies for* 1° x 1° *Blocks.* A preliminary study was made to determine the obtainable accuracy for 1° x 1° squares. The mean values for 25 1° x 1° blocks were computed from two symmetrical east-west profiles across each block. In the South-Central test area the representation error for two such profiles is practically zero and the statistical representation error is only ±0.6 mgal. An average standard error of ±29.7 mgal was obtained for the LaCoste and Romberg and ±9.7 mgal for the Askania gravimeter.

V

From the preliminary reduction and analysis of the measurements in the South-Central test area it can be seen that the Askania-Graf instrument performed better than the LaCoste and Romberg. However, it must be noted that the LaCoste and Romberg results are derived from both east and west profiles, the Askania results contain only west profiles. The effect of the same ground speed error is larger in east direction, therefore, the comparison cannot be considered as final conclusion. It is true, however, that profile comparisons under identical flight conditions are still in the favor of the Askania instrument. Both instruments are acceptable for global surveys provided navigation errors are reduced.

The errors from present aircraft navigation are excessive where cartographic corrections obtained from existing map coverage and aerial photography are not possible. Estimates for cartographically corrected navigation accuracies achieved during test flights are:

ground speed	±1.1 to 1.5 knots
azimuth	±0.2 to 0.4 degree
position	±0.3 to 0.5 nautical mile

For global surveys requiring about +8 mgal accuracy for 5° x 5° mean anomalies the desired navigation accuracies would be:

ground speed	±0.5 knot
azimuth	±0.1 degree
latitude	±1.5 minutes of arc

The random stabilization error of the ART-57 platform is ±3.5 minutes of arc according to simulation tests. To obtain more accurate gravity data it is required that the stable platform be aligned with respect to the local vertical or the apparent vertical to an accuracy of one minute of arc. The apparent vertical is the direction of the resultant between gravity, Coriolis effect, and other constant effects, therefore, postflight corrections to the local vertical can be computed.

The present computer program for data reduction is not final. The vertical acceleration problems and spectral analyses of gravity data are being studied to establish optimum filtering method. Theoretical studies on the downward continuation of gravity have been made at Ohio State University, and the results are published. The application of these studies for the observed material will be done at AFCRL after the final filtering method is determined.

The instrumentation research to improve airborne gravity sensors and related instruments is continuing. To resolve the critical navigation problems and improve gravity sensor stability, M.I.T., under contract to AFCRL, investigates various inertial guidance system components for possible use in aerial gravimetry. As a result, a pendulus integrating gyro accelerometer was laboratory tested and converted into a gravity sensor. This sensor is prepared for flight testing which will start in October 1966.

The ART-57 platform is inadequate to support accelerometer type of gravity sensors, in addition the use of separate stable platforms for two or three different instruments introduces a variable in the comparison of the results. As a solution, an airborne platform is being developed for AFCRL by Northrop Nortronics that is capable of supporting two or three sensors. The platform design and quality of components will provide stabilization with respect to the local vertical within 3 to 10 seconds of arc in the presence of horizontal accelerations up to 100 gals.

Bell Aerosystems Company developed a shipboard gravity-measuring system with an accelerometer sensor. The system was developed under contract to the Naval Oceanographic Office. The first tests have been completed very satisfactorily and additional tests are scheduled by the Coast and Geodetic Survey (ESSA) for the end of 1966. The Air Force is considering testing this system in an aircraft when the shipboard tests are completed.

Identification of Deflection of the Vertical Using an Inertial System

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1. INTRODUCTION

The deflection of the vertical which is the angular difference between the plumb-bob vertical and the normal to the reference ellipsoid (geodetic vertical) is a useful geological parameter for the detection of large mass variations. On land the deflection can be evaluated by torsion balances, but at sea the moving base provided by the ship makes the use of such instruments unfeasible. At sea, one might use a gravimeter to measure the variation in the vertical component of g and compute the deflection of the vertical by using Stokes' theorem. This method has limited use. It requires that an area of several hundred miles radius be surveyed to determine the deflection at one point. Another technique is to compare a star sight (referenced to the astronomic vertical) with a geodetic reference (Loran C, Lorac) and attribute the error to vertical deflection. The accuracy of such a device is still questionable considering the present state-of-the-art in instrumentation. This paper shows how an inertial navigator can be used in conjunction with a geodetic reference to indicate the deflection of the vertical.

In the inertial navigator as with any other type of servomechanism, the output will show some distortion of the input because of the response time of the servomechanism. In the case of measuring vertical deflections due to gravity anomalies (in this paper "vertical deflections due to gravity anomalies" will be referred to as "gravity deflections"), the input waveform, as viewed by the inertial navigator, varies as a function of the ship's speed. The intent of this paper is to show how, in a restricted case, the parameters of a vertical deflection waveform can be recovered. The form chosen is

$$\varphi(t) = a(1 - \cos \omega_\varphi t) \quad 0 < t \leq \frac{2\pi}{\omega_\varphi} , \tag{1}$$

where

a = coefficient of vertical deflection, and
ω_φ = frequency of vertical deflection input.

This waveform is a reasonable one for describing the vertical deflections in the direction of crossing of the continental shelf.

First it will be shown how such vertical deflections display themselves as position error responses from an inertial navigator. Then a recovery scheme will be described for obtaining parameters a and ω_φ from the position error responses. It will be shown theoretically that the parameters a and ω_φ can be exactly recovered when no other error sources exist in the inertial system—in a noise-free case. In actual practice, position data from an inertial navigation system is contaminated by other sources of error. Since the inertial system tracks the local vertical, the magnitude of the tilt angle recovered from the position data can only be as good as the ability of the system to track the local gravity vector in the presence of other noise (in this paper the gravity deflections are considered as signals while all other inertial system error sources are considered to be noise) inputs to the system. The use of the system. The use of the vertical deflection parameters recovery scheme in conjunction with noisy position data for a real case is illustrated at the end of this paper.

It is emphasized that although the example chosen is restricted, the general recovery technique can be applied to other waveforms. For general surveying more sophisticated filtering techniques would be in order. The example chosen does show that the state-of-the-art is such that the inertial navigator can now be thought of as a useful geodetic tool.

2. DYNAMIC CHARACTERISTICS

Before delving into a specific analysis of the problem, it will first be shown how a complete 3-gimbal inertial system error diagram can be reduced to two independent Schuler loops for the problem at hand. Figure 1 shows the complete three-axis inertial navigation system error diagram. See Gelb [1965] for a complete derivation of error equations and a block diagram for the 3-axis inertial navigator.

The signal inputs considered in this paper are errors in acceleration caused by erroneous indication of the vertical in the case of gravity anomalies, $g\varphi_y$ and $g\varphi_x$, where φ refers to the deviation of the local gravity vector from the normal to the reference ellipsoid. All other error sources are considered to be zero (gyro drift rates, gimbal offsets, etc.).

It is seen that the transmission of the input considered from the X accelerometer Schuler loop to the X gyro is identically zero. Similarly the transmission of the input from the Y accelerometer Schuler loop to the Y gyro is identically zero. Hence for the inputs considered, the Schuler loops are decoupled and can be treated independently. The position errors shown in figure 1 are expressed in minutes of arc. If these errors are to be expressed in nautical miles, then longitude error must be multiplied by cos L. This has the effect of making both of the Schuler loops identical, as shown in figure 2, where position error (latitude or longitude) is now represented by δp. Note that there exists velocity feedback in the system to provide a mechanism for the dissipation of undamped second-order sinusoids which would result from any disturbance to the system [Gelb, 1965]. The velocity feedback consists of a first-order filter resulting in a third-order damped inertial system.

The transfer function from gravity deflection to position error is

$$\frac{\delta p}{\varphi} = \frac{-g/R(s + C_2)}{s^3 + (C_1 + C_2)\, s^2 + g/R\, s + C_2\, g/R}. \tag{2}$$

The gains C_1 and C_2 are defined to yield a third-order loop with real and complex pole decay factors all equal. Following this procedure, the characteristic equation of the loop,

$$\Delta = s^3 + (C_1 + C_2)\, s^2 + g/R\, s + C_2\, g/R\,, \tag{3}$$

takes the form

$$\begin{aligned}\Delta &= (s + \zeta\omega_n)(s^2 + 2\zeta\omega_n s + \omega_n{}^2) \\ &= s^3 + 3\zeta\omega_n s^2 + (2\zeta^2\omega_n{}^2 + \omega_n{}^2)\, s + \zeta\omega_n{}^3.\end{aligned} \tag{4}$$

Equating coefficients results in

$$\begin{aligned} C_1 + C_2 &= 3\zeta\omega_n\,, \\ g/R &= w_n^2 + 2\zeta^2\, w_n^2\,, \text{ and} \\ C_2\, g/R &= \zeta\omega_n^3\,. \end{aligned} \tag{5}$$

By picking a ζ, the variables ω_n, C_1, and C_2 can immediately be evaluated. Note that were the real pole not located at the projection of the complex conjugate poles, picking a ζ does not uniquely define C_1 and C_2. Using these dynamic relationships, the system response to gravity deflections and, conversely, the recovery of the gravity deflections from a given system response can be investigated.

3. ANALYSIS

The results of an analysis to recover the parameters of the model of gravity deflection are given by

$$\varphi(t) = a(1 - \cos\omega_\varphi t), \qquad 0 < t \le \frac{2\pi}{\omega_\varphi}. \tag{6}$$

The known quantities in the analysis are the inertial navigator dynamics (Section 2) and ship's velocity, v. The unknown quantities are the coefficient of the gravity deflection waveform a, and the length of the deflection waveform λ, related to the frequency ω_φ as follows:

$$\lambda = vt \quad (v \text{ known}) \tag{7}$$

$$\omega_\varphi = \frac{2\pi}{t} \tag{8}$$

or

$$\omega_\varphi = \frac{2\pi v}{\lambda}$$

$$\lambda = \frac{2\pi v}{\omega_\varphi} \tag{9}$$

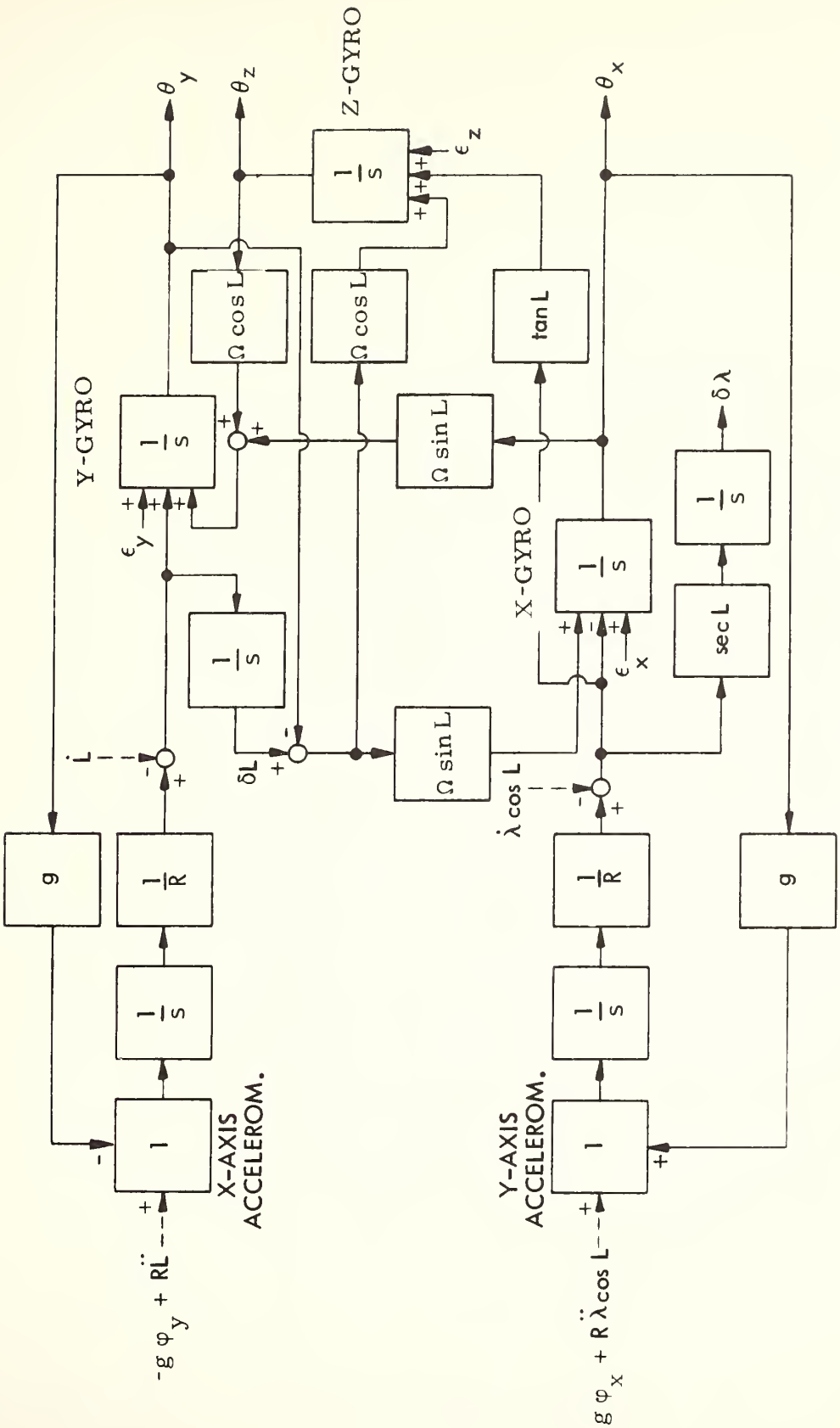

FIGURE 1.—Three-axis inertial navigator error diagram.

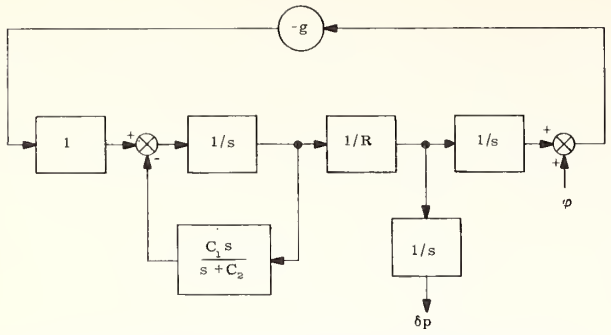

FIGURE 2.—Schuler error block diagram showing gravity deflection imput and position error output.

Thus, by knowing the ship's velocity, v, and inferring the frequency of the gravity deflection, ω_φ, the wavelength and amplitude of the gravity deflection can be deduced.

Before proceeding with the recovery phase of the analysis, some typical position error responses due to one cycle of the anomaly waveform (1-cos $\omega_\varphi t$) will be presented in order to get a feel for the change in position response due to a change in frequency of the deflection input.

3.1 *System Response to Vertical Deflections Due to Gravity Anomalies.* Since an inertial navigator is basically a linear system, the parameter a can be normalized at $a = 1/2$ min and responses can be investigated as a function of varying frequency ω_φ. Equations (7) through (9) defined ω_φ as a function of ships velocity and deflection wavelength. Table 1 presents a range of wavelengths and corresponding frequencies for ships velocities of 5 and 10 knots.

Figure 3 shows position error plots vs. time over a range of gravity deflection frequencies between 12.56 rad/hr and 1.57 rad/hr (Schuler frequency is 4.46 rad/hr). The responses shown are for a system with the following dynamics

$$\zeta = .29$$

$$\omega_n = 4.14 \text{ rad/hr}$$

$$C_1 = 2.57 \text{ rad/hr}$$

$$C_2 = 1.02 \text{ rad/hr.}$$

By scanning this sequence of curves, certain characteristics of the position transient response are immediately apparent.

1. For deflection frequencies much higher than the Schuler frequency ($\omega_\varphi \gtrsim 8$ rad/hr), there is attenuation in the peak magnitude of the position response with respect to the gravity deflection input. $(\varphi(t)_{max} = 1)$.

2. For deflection frequencies in the range of Schuler frequency ($3 \lesssim \omega_\varphi \lesssim 8$) there is magnification in the peak magnitude of the position response with respect to the deflection input.

3. For low deflection frequencies with respect to Schuler frequency ($\omega_\varphi \approx 1$ rad/hr) the gravity deflection waveform is passed relatively undistorted and reproduced at position.

4. As the deflection frequency passes from higher to lower than the Schuler frequency the ratio of second to first overshoot of the position response decreases along with the ratio of time duration of second to first overshoot.

The collation of these characteristics form the crux of the gravity deflection parameter recovery scheme. While the curves in this section are shown for particular system dynamics, the conclusions would hold across the board for any change in ζ, ω_n, C_1, and C_2, the only difference being in the amount of magnification and attenuation, as will be seen in the next section.

3.2 *Recovery of Gravity Deflection Parameters from Navigator Position Data.* In the pre-

Table 1.—Frequencies of Gravity Deflection Model over a Range of Wavelengths and Ship's Velocity $(\omega_\varphi = \frac{2\pi v}{\lambda})$

Wavelength - λ (nm)	Deflection frequency - ω_φ (rad/hr)	
	(v = 10 knots)	*(v = 5 knots)*
1	62.8	31.4
2	31.4	15.7
5	12.56	6.28
7.04	8.92	4.46 (Schuler)
10	6.28	3.14
14.08	4.46 (Schuler)	2.23
15	4.17	2.09
20	3.14	1.57
30	2.09	1.05
40	1.57	.785
50	1.26	.628
60	1.05	.524
70	.888	.449
80	.785	.392
90	.698	.349
100	.628	.314

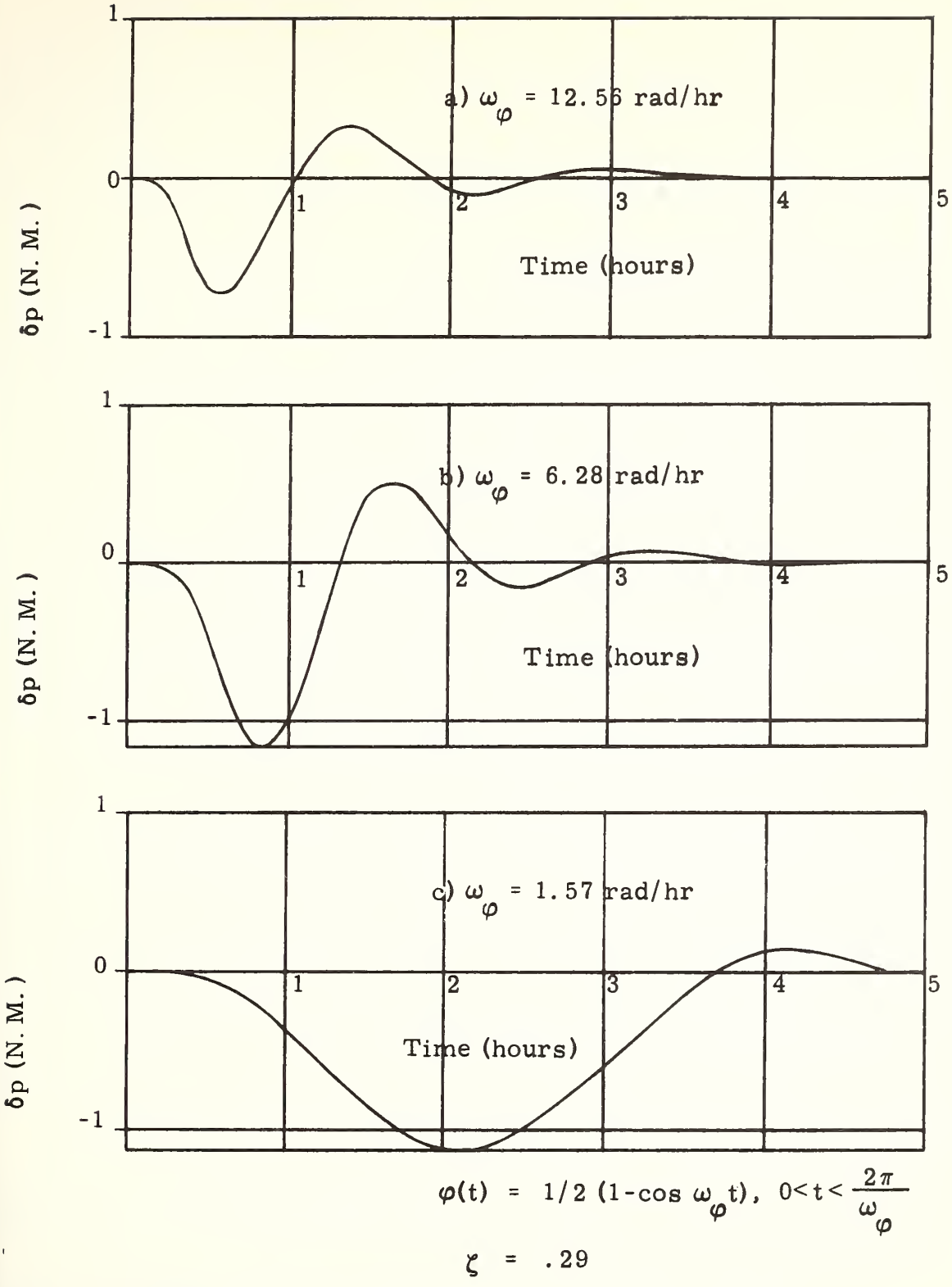

FIGURE 3.—Position error vs. time for range of gravity deflection frequencies.

vious section the general characteristics of position error responses to gravity deflection disturbances of the form $a(1-\cos \omega_\varphi t)$ were discussed. In this section a graphical method of recovering the gravity deflection parameters a and ω_φ from position error responses is presented. While the curves generated for the recovery of the parameters are of necessity purely theoretical and based on the existance of no other navigator error sources (gyro drift rate, speed log errors, water currents etc.), they can also be applied to noisy position data. The effectiveness of this recovery technique naturally diminishes with increased noise. More will be said about this point later. Recovery of gravity deflections will be more effective in large anomaly areas since there the "signal to noise" ratio will be much larger. Application of the recovery scheme to a piece of actual noisy position data (normalized for security reasons) will be shown at the conclusion of this section.

The recovery scheme for the deflection parameters, a (coefficient of gravity deflection waveform) and ω_φ (frequency of gravity deflection input), is graphical and depends upon the fact that the system dynamics are known. If in addition, λ (wavelength of gravity deflection) is desired then ship's velocity must also be known.

The key to the recovery scheme is knowledge of the system damping ratio ζ. From a knowledge of ζ all other parameters in the inertial navigators dynamical system can be evaluated from Eq. (5). Thus the deflection parameter recovery scheme has been analyzed over a range of ζ and corresponding ω_n, C_1 and C_2 as in table 2.

Table 2.—Dynamics Used for Gravity Deflection Recovery Scheme

ζ	ω_n(rad/hr)	C_1(rad/hr)	C_2(rad/hr)
.0674	4.46	.605	.296
.2	4.29	1.776	.794
.29	4.14	2.57	1.02
.68	3.21	5.415	1.135

Figures 4-7 show curves of the graphical method of evaluating the parameters of a gravity deflection for the previously designated navigator dynamics. Let us now consider how to use these graphs, using figure 6 as an example since the corresponding position responses are shown for $\zeta = .29$.

Step 1. Determine the ratio of the peak magnitude of the second overshoot to the peak magnitude of the first overshoot from the position error response curves, called $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max). These are plotted as a function of ω_φ in figure 6.

Step 2. Determine the ratio of time duration of the second overshoot to the first overshoot, that is, the time between the first and second zero crossing to the time between $t = 0$ and the first zero crossing, called $\frac{T_2}{T_1}$. These are plotted as a function of ω_φ in figure 6.

Step 3. Having determined the previous two ratios from the position response curves, slide over the vertical axis to the corresponding ratio curves in figure 6, then down to the horizontal axis to pick off the corresponding ω_φ. In the noise-free case, steps 1 and 2 give the same frequency. This may seem redundant. However, for position data corrupted by noise, steps 1 and 2 give different frequencies as will be seen in the example at the conclusion of this section. The value of a is now determined.

Step 4. From the curve of δp^1 (max), pick the the value of δp_1 (max) in figure 6 corresponding to ω_φ of step 3. The curve of δp_1 (max) is a curve of peak position overshoot vs. ω_φ for a theoretical input $\varphi(t) = 1/2\,(1 = \cos \omega_\varphi t)$, where the reference $a = 1/2$ min. Form the ratio

$$\frac{1/2 \text{ min}}{\delta p_1(\max)\ (\text{nm})} = \frac{a \text{ min}}{\delta p_s(\max)\ (\text{nm})} \qquad (10)$$

where $\delta p_{s\,(\max)}$ (nm) is the peak position error due a gravity deflection that would be taken from actual navigator position data.

Step 5. Solve for a in Eq. (10). This is the coefficient of the gravity deflection waveform.

Step 6. Knowing ω_φ and ships velocity, v, we could go to Eq. (9) and solve for the wavelength, λ.

ζ = .067

ω_n = 4.46 rad/hr.

C_1 = .605 rad/hr.

C_2 = .296 rad/hr.

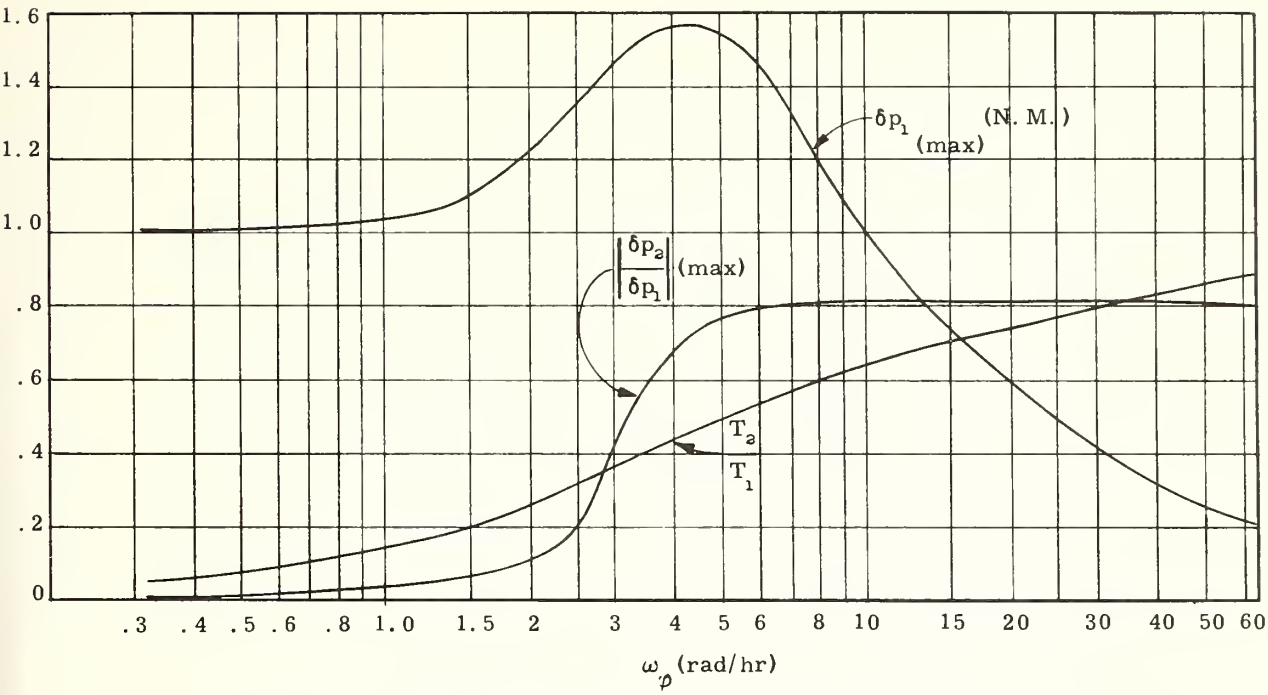

FIGURE 4.—Graphical evaluation of gravity deflection parameters, ζ = 0.067.

Example. As an example let us consider Fig. 3b to be the response to some unknown gravity deflection. It is desired to determine a and ω_φ knowing ζ = .29.

Step 1: $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) = $\frac{.5 \text{ (nm)}}{1.16 \text{ (nm)}}$ = .43.

Step 2: $\frac{T_2}{T_1} = \frac{.8 \text{ hrs.}}{1.4 \text{ hrs.}} = .57.$

Step 3: From figure 6 where ζ = .29, look up the ratio .43 on the vertical axis, slide over to the corresponding $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) curve and down to the horizontal axis to determine ω_φ. However note that the $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) curve is relatively flat over the band of frequencies $5 < \omega_\varphi < 60$. Thus the redundant information is used by looking up the ratio .57 on the vertical axis, slide over to the corresponding $\frac{T_2}{T_1}$ curve and down to the horizontal axis to determine $\omega_\varphi \cong 6.3$ rad/hr. (The two ratios should give the same frequency since a noise free case was chosen where it is known *a priori* that ω_φ = 6.28 rad/hr.) For this example one would choose ω_φ = 6.3 rad/hr since this is a noise free case. In general, two different frequencies will occur for noisy data. The users would then do best to interpolate between them.

Step 4: From the $\delta p_{1\,(\max)}$ (nm) curve for ω_φ = 6.3 rad/hr,

$$\delta p_{1\,(\max)} \text{ (nm)} \cong 1.2 \text{ nm}$$

is obtained from the vertical axis. From the position error curve (fig. 3b for our example)

$\zeta = .2$

$\omega_n = 4.29$ rad/hr.

$C_1 = 1.78$ rad/hr.

$C_2 = .79$ rad/hr.

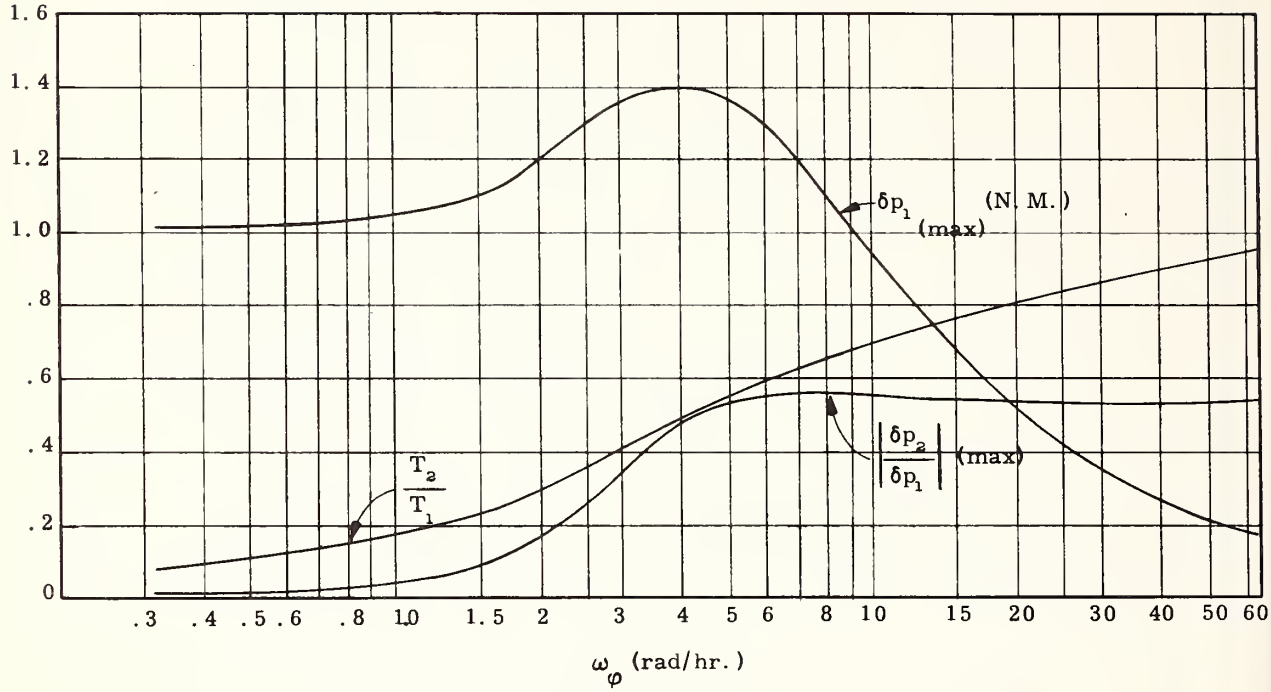

FIGURE 5.—Graphical evaluation of gravity deflection parameters, $\zeta = 0.2$.

$$\delta p_{s\,(\max)}\,(nm) \cong 1.2\ nm.$$

Step 5: From Eq. (10) results in $a = 1/2$ min which is the coefficient of the deflection waveform giving us the response of figure 3b.

Step 6: From Eq. (9).

$$\lambda = \frac{2\pi v}{\omega_\varphi}.$$

Let $v = 10$ knots. From Step 3, $\omega_\varphi = 6.3$ rad/hr, hence $\lambda \cong 10$ nm, the wavelength of the gravity deflection.

Comments on figures 4-7. By investigating the pattern of graphs in figures 4-7 as ζ varies from .067 to .68 the following characteristics are noted.

1. The $\frac{T_2}{T_1}$ curves increase with an increase in ζ and are single valued over all ω_φ.

2. The $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) curves decrease with an increase in ζ and are nearly flat for $\omega_\varphi \gtrsim 6$ rad/hr.

3. The $\delta p_{1\,(\max)}$ curves decrease with an increase in ζ and peak at a frequency slightly less than ω_n.

4. At low deflection frequencies, the ratios $\frac{T_2}{T_1}$ and $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) are small, the $\delta p_{1\,(\max)}$ curves level off at 1 (nm), and the gravity deflection waveforms should be completely reproduced at position (see fig. 3c).

5. At deflection frequencies around frequency, ω_n, the ratios $\frac{T_2}{T_1}$ and $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) increase, the

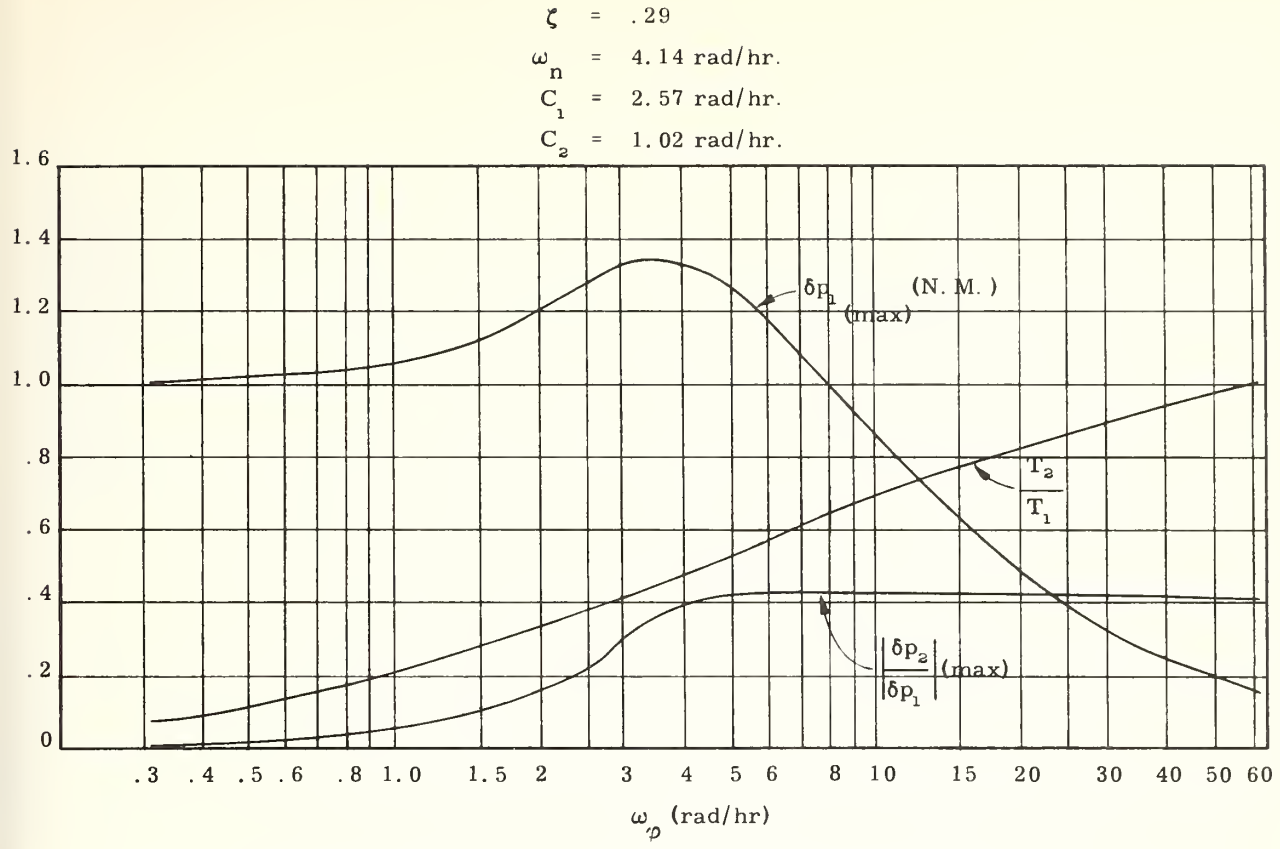

FIGURE 6.—Graphical evaluation of gravity deflection parameters, $\zeta = 0.29$.

δp_1 (max) curves are magnified, and the gravity deflection waveforms are not distinguishable from the position responses (see fig. 3b).

6. At high deflection frequencies, the $\frac{T_2}{T_1}$ and $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) are large (depending on the ζ), the δp_1 (max) curves are attenuated, and the gravity deflection waveforms are not distinguishable from the position responses (see fig. 3a).

7. Since the $\frac{T_2}{T_1}$ curves are single valued over the range of deflection frequencies, the question naturally arises as to the necessity of the $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) curves. The reason for the two curves is that in practice the position data will be noisy and the two ratios will not give the same deflection frequency. Thus, the user can interpolate between the frequencies obtained from each ratio measurment and come up with a satisfactory value of ω_φ. An example at the end of this section using noisy position data will illustrate this point.

8. While the recovery scheme graphs presented in this section are only for certain system damping ratios, the previous comments on these graphs will allow the reader to interpolate between graphs and make the recovery scheme applicable for all system damping ratios.

Example of Recovery Scheme Using Noisy Position Data. To fix ideas on the use of the graphs to recover the gravity deflection parameters, an actual piece of noisy position data has been selected. For security reasons the scale of the position error has been normalized to unity. Figure 8 shows the system error response at longitude of a crossing of a known gravity deflection area. The system damping ratio is .29. The ship's velocity was 9 knots.

The dynamics of long-term inertial-system error propagation are governed by an undamped 24-hour oscillator at latitude and heading, and additionally by an open loop integration at longitude [Gelb, 1965]. To more accurately determine the

ζ = .68

ω_n = 3.21 rad/hr.

C_1 = 5.42 rad/hr.

C_2 = 1.14 rad/hr.

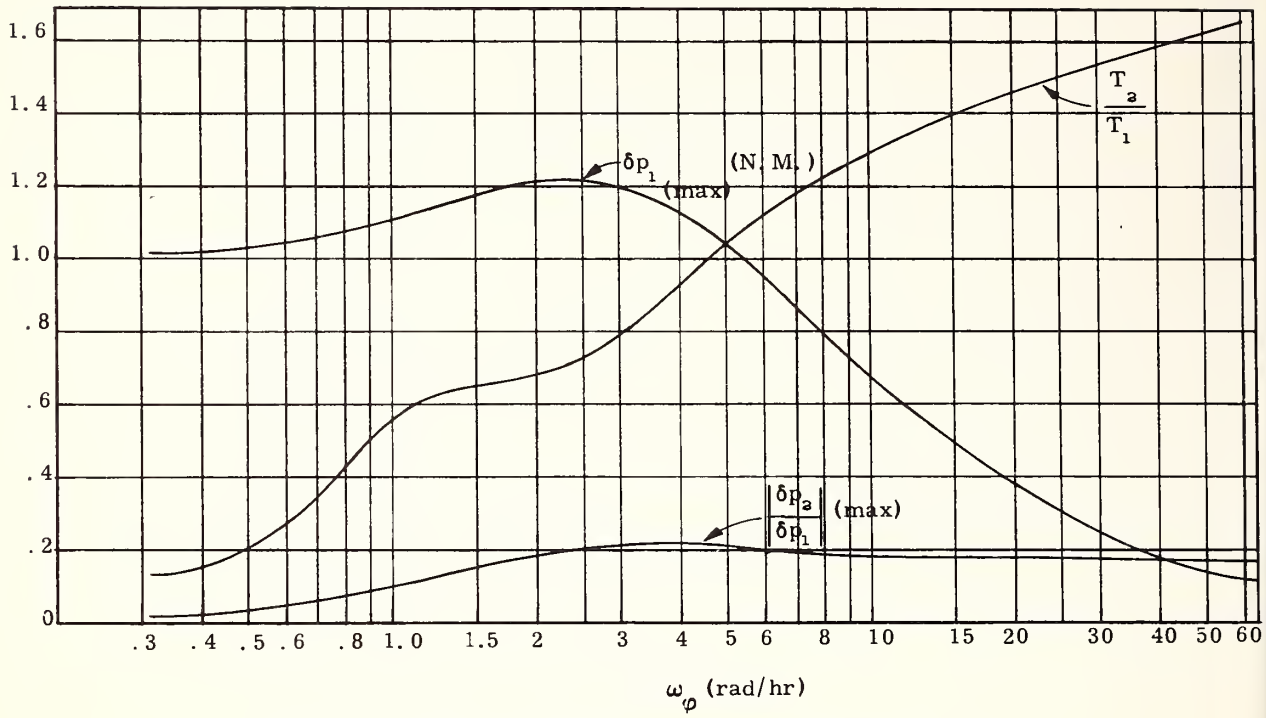

FIGURE 7.—Graphical evaluation of gravity deflection parameters, ζ = 0.68.

pickoff points for the gravity deflection recovery scheme, a 24-hour sinusoid could be fit and subtracted from latitude position data [Friedman et al., 1964], and a 24-hour sinusoid plus ramp could be fit and subtracted from longitude position data. This would remove the effect of bias drift rates and gimbal offsets from the position error responses, making more prevalent on the position error response the effect of a gravity deflection. Previously it was shown that gravity deflections do not induce 24-hour oscillations. In figure 8 the inertial system longitude error is being considered. Thus the 24-hour sinusoid and ramp have been smoothed over, clearly delineating the Schuler response to the gravity deflection. The steps leading up to the identification of the gravity deflection parameters will now be shown.

1. Consider the position response caused by the deflection to start at t = 17.5 hrs. Consider the first zero crossing to be at t = 20.5 hrs. and the second zero crossing to be at t = 20.75 hrs., thus

$$\frac{T_2}{T_1} = \frac{.25}{3.0} = .083.$$

2. From figure 8 the ratio of the peak of the second overshoot is

$$\left|\frac{\delta P_2}{\delta P_1}\right| \text{ (max)} = \frac{.08}{.667} = .12.$$

3. From figure 6 for T_2/T_1 = .083 there is no corresponding ω_φ. For $\left|\frac{\delta p_2}{\delta p_1}\right|$ (max) = .12 ω_φ = 1.5 rad/hr. Thus ω_φ = 1.5 rad/hr is chosen.

4. From the δP_1 (max) curve in figure 6 pick off a value of δP_1 (max) = 1.125 nm due to a test value of a = 1/2 min at ω_φ = 1.5 rad/hr.

5. Now solve for the coefficient of the vertical deflection waveform a from Eq. (10) where

$$\delta P_1 \text{ (max)} \text{ (nm)} = 1.125 \text{ nm}$$

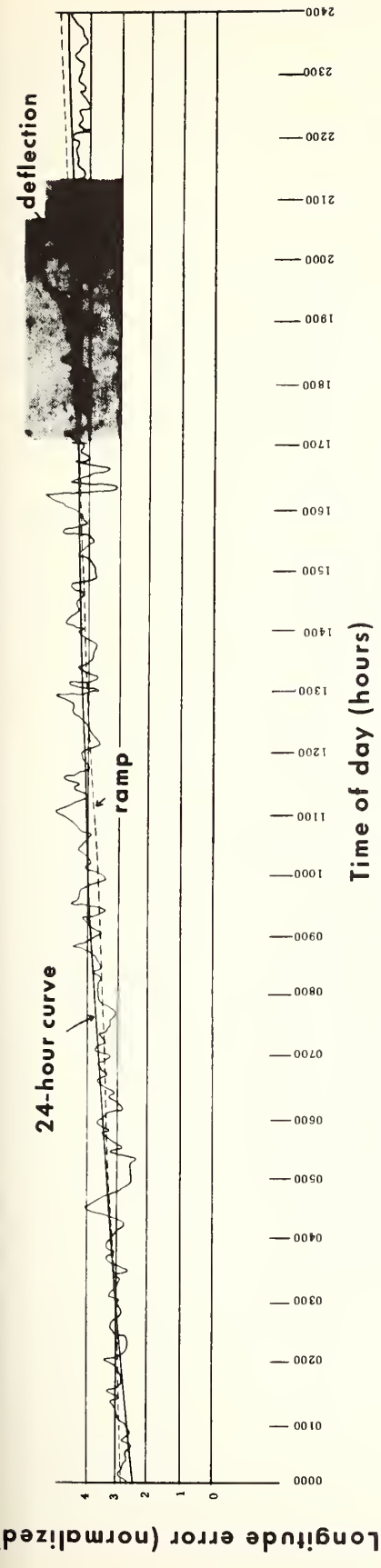

FIGURE 8.—Typical position error response caused by deflection of the vertical.

and

$$\delta P_{s\,(\max)}\ (\text{nm}) = .667 \text{ nm}$$

from the position data in Eq. (10). Thus,

$$a = \frac{1/2\,(\delta P_s)}{\delta P_1} = \frac{1/2\,(.667)}{1.125} = .296 \text{ min.}$$

(normalized)

The normalized deflection waveform coefficient is therefore $a = .296$ min for $\omega_\varphi = 1.5$ rad/hr. The gravity deflection waveform is thus

$$\varphi(t) = .296\,(1\text{-}\cos 1.5\,t)$$

for this piece of actual inertial system data.

6. The ship's velocity is given as 9 knots. The deflection wavelength is given by Eq. (9) as

$$\lambda = \frac{2\pi V}{\omega_\varphi} = \frac{(2\pi)(9)}{1.5} = 37.5 \text{ nm.}$$

A gravity survey was conducted using a La-Coste-Romberg gravity meter which measures gravity anomalies as contrasted to gravity deflections and requires a significant amount of surveying as against one pass of the inertial navigator. The gravity deflection can then be determined from the gravity anomaly data by use of Stokes' theorem Heiskanen and Vening Meinesz, 1958]. The resultant gravity deflection coefficient determined was .332 min, not significantly different from the values obtained by the graphical method in considerably shorter time. Thus it appears that the vertical deflection recovery scheme using inertial system position data has the advantage of speed over other methods, and in large anomaly areas, where the deflection waveform can be considered to be mathematically modeled as

$$\varphi(t) = a(1\text{-}\cos\,\omega_\varphi t),$$

does not suffer greatly for loss of accuracy.

CONCLUSIONS

A graphical method of identifying the parameters of a gravity deflection profile of the form $a(1 - \cos\,\omega_\varphi t)$ by observation of inertial system position error responses has been developed. The method does not give the absolute deflection with respect to the reference ellipsoid, but only the relative change from one geographic

position to another due to the inability of the navigator to perfectly track the local vertical. The effectiveness of the graphical recovery technique diminishes with an increase in noise (other error sources) and in the presence of noise is perhaps a best indicator of "large" gravity deflections.

The use of the graphical techniques in identifying the parameters a (coefficient of gravity deflection waveform) and ω_{φ} (frequency of gravity deflection input) dictate that the dynamics of the inertial navigator be known. In addition, if the wavelength of the gravity deflection is desired, the ship's velocity must also be known and used in conjunction with Eq. (9).

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of Dr. K. S. Narendra, Yale University, in the preparation of this paper.

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Underwater Gravity Measurement in the Baltic Sea and in the Barents Sea

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Large areas on the continents have been covered with a uniform net of gravity stations. For geodetic purposes a net over the whole globe is necessary. Hence gravity surveys at sea are now most important. There are at least four methods for gravity surveys in the sea:

1. Vening Meinesz pendulum apparatus
2. Bottom gravimeters
3. Registration of gravity aboard a ship
4. Registration of gravity in an airplane.

The Vening Meinesz pendulum apparatus was the first and has been much used. It has given many important results. However, today it is too slow and expensive.

Bottom gravimeters have been used in the Gulf of Mexico, the Adriatic Sea, and the Baltic. This method has many advantages compared with the others and seems to be the most accurate method. The registration of gravity aboard a surface ship has been largely used in the last years, but few results have been published. The areas where bottom gravimeters have been used offer good possibility to study the sea surface gravimeters as well as the airborne gravimeters.

There are large areas where sea bottom gravimeters can be used. The total area on continental shelves with a depth less than 200 m is 5 percent of the Earth's surface or 17 percent of the dry-land surface. The accuracy of gravity measurement is nearly the same in the sea bottom as on the dry land. The accuracy of the depth measurement with echo sounding is better than ± 1 m. The accurate coordinates of gravity stations can in many areas be determined with the Decca system. Near the coasts the coordinates seldom involve serious difficulties.

As examples of such surveys the measurements of the Finnish Geodetic Institute in the Baltic Sea in 1956 and in the Barents Sea in 1957 are referred to. It was advantageous that the expeditions carry out many types of works. Oceanographical, geological, and other research work are carried out simultaneously. The gravimeter was a Gulf-underwater gravimeter, kindly lent by Gulf Research and Development Co. The depths were measured with Atlas-Echograph. The simultaneous determination of water temperature and salinity at different depths, by the oceanographers, were used to correct the soundings. The controlled standard error of depth measurements was ± 0.7 m. The coordinates were determined, with Decca-system where possible, and near the coasts with resection. In the Barents Sea the station coordinates were the largest error sources of the gravity anomalies. The standard error was estimated to be ± 1 mgal. The carrier was the research vessel m/s *Aranda* of the Institute of Marine Research.

The method of observation was as follows. The echo sounder was continuously running to study the sea bottom. At a suitable place the ship was stopped and a marking buoy was anchored on the spot. The ship was held at the side of the buoy during the whole measuring period—about 20 min.—with the aid of the propellers, the forescrew, and the rearscrew of the ship. In this way an accuracy of ± 20 m was usually attainable. The calibration constant of the gravimeter was derived on the basis of observations in the harbors where the gravimeter was read every third day during the Baltic measurements and once a week during the Barents Sea measurements. The closures were regular and small. The daily drift was + 0.3 mgal/day. Altogether 178 stations were measured in the Baltic during two months and 21 in the Barents Sea. The mean depth of the gravity stations was 66 m, 36 stations were measured deeper than 100 m, and the deepest station was 151 m. The free-air gravity anomalies are given in the two maps shown as figures 1 and 2.

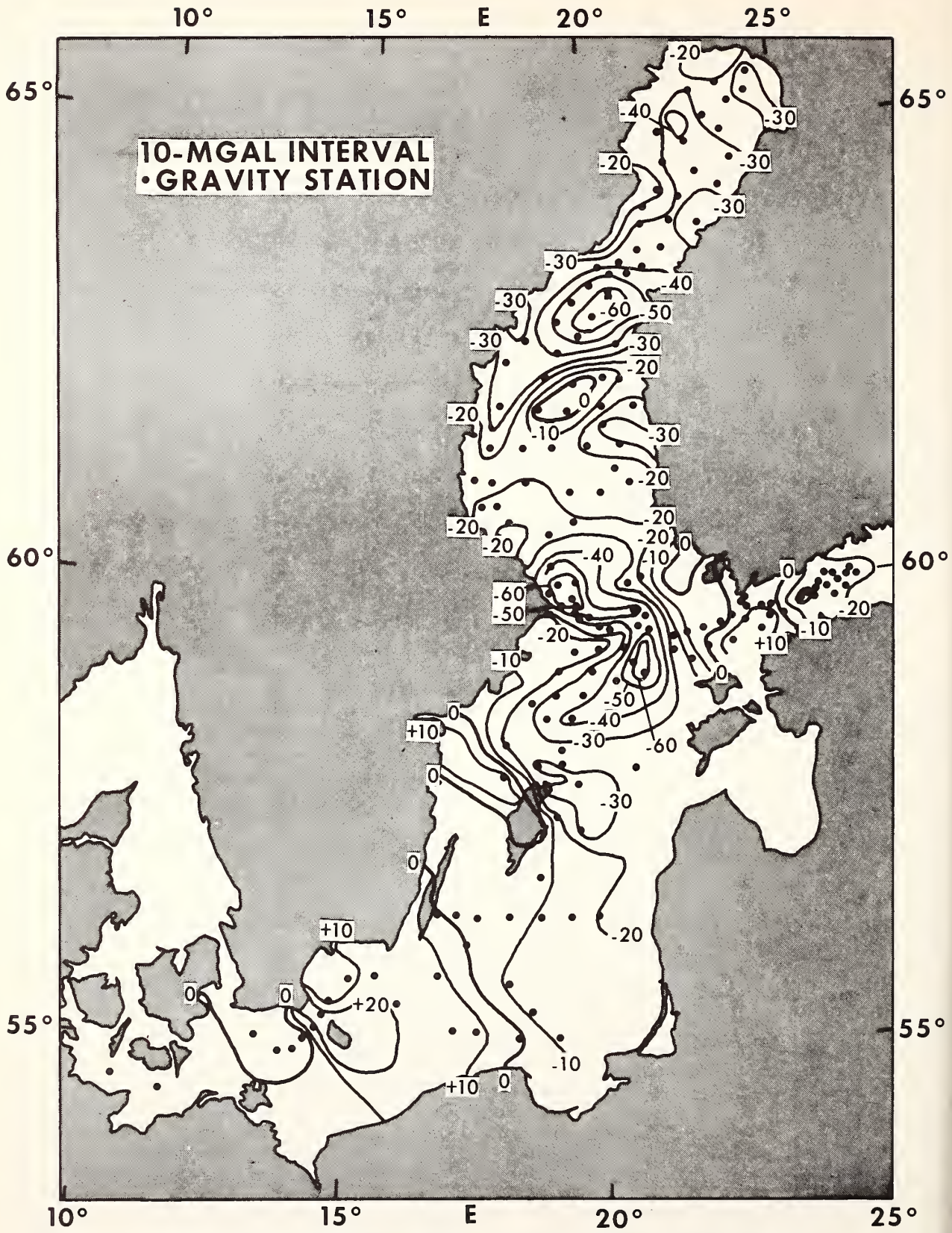

FIGURE 1.—Free-air gravity anomalies, Baltic Sea, 1956. (Finnish Geodetic Institute)

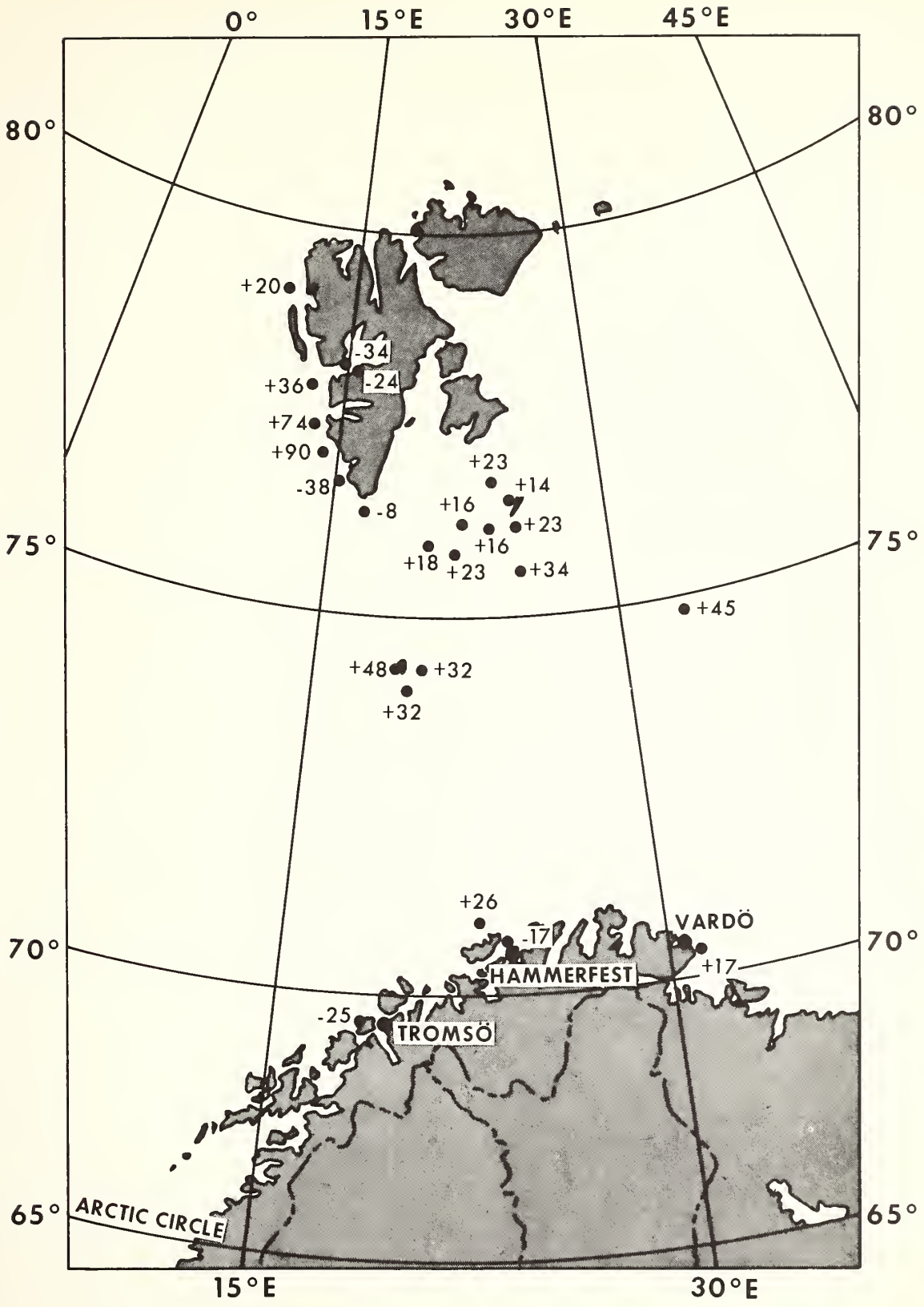

FIGURE 2.—Free-air gravity anomalies, Barents Sea, 1956. (Finnish Geodetic Institute)

Session IV Panel Discussion

C. A. WHITTEN, *Chairman*, (U.S. Coast and Geodetic Survey (ESSA), Rockville, Md.).

CAPT. MOITORET: This is not a question, I just want to be sure that everyone who is present today realizes that there has been a terrific breakthrough—maybe you do not recognize it. When the last activities report of the Coast and Geodetic Survey came out, I noticed that they had tested a new Bell Gravity Meter. Today, Dr. Orlin, my friend, was frank enough to admit on the stage that the Navy had something to do with this gravity meter. I want to thank him for this breakthrough because we did not have very much to do with it. All we did was to put up nine-tenths of the money, do the contracting, provide the equipment, test it out and so on. Thanks very much.

DR. ORLIN: By the way, that was to pay you back for the picture you took of Coast Survey officers being trained by Navy personnel.

MR. GUMERT: The Navy plans to test a gravity meter in an aircraft over the Patuxent Naval Range.

MR. SZABO: I have been informed—and this is the second-hand information—that for the airborne tests of the Bell System, the original intent was to show two good steps. A more substantial longer test program will be initiated. That is all that I know about the air tests at the present time.

DR. MORITZ: First a comment and then a question. The comment concerns the significance of the papers by Mr. Szabo and Mr. Bradley. I was interested in the similarity. One dealt with the magnitude of the gravity vector and the other with the direction of the gravity vector. These are prime geodetic problems. Can the two techniques be combined into a unified system for measuring the magnitude and direction of the gravity vector? Would the two speakers comment on this possibility?

MR. SZABO: You stated previously that you are trying to measure the magnitude and the vertical components of the gravity vector. You can get satisfactory measurements regarding deflection, and we could combine the two techniques in order to obtain the full gravity vector. This definitely would promote the state-of-the-art in this area. I followed with interest the paper by Mr. Bradley and I hope I will have a chance to examine it and the development described in it to see how we can combine the two techniques.

MR. BRADLEY: I would like to comment on that. Yes, you can combine them. Essentially, the navigator erects a stable platform on which the instrument is mounted—only it is a platform with no position indicator on it. Combine a complete navigator with this platform giving you position information. If you mount your gravity meter on top of the platform, you should have the complete package. You should be able to measure the magnitudes in the vertical direction and use the same technique that I mentioned for getting the actual deflection, or the direction of the vertical.

DR. WING: I have an additional comment. If you have an inertial platform good enough to measure the deflection of the vertical, then you have a platform on which you can mount a horizontal accelerometer and measure the Eötvös correction. You are actually solving the two problems with one stable platform.

MR. SZABO: I have an additional comment. At the present time we are using Doppler techniques for navigation rather than inertial systems. However, we are going in the direction of inertial systems, because of our experience in airborne measurements. The ideal package would be an inertial navigational and stabilization system with a sensor to measure the vertical component of the gravity vector. This system would then perform the navigation and perform the stabilization needed to obtain the required accuracy. The stabilization system can be used to weed out the wild data which are detrimental to the system. The vertical accelerometer could provide the vertical component of the gravity vector, for we know that at the present time this is one aspect of inertial navigation that has been successful. The problem that we must resolve is: Can these systems measure the physical quantities to the required accuracy?

FROM THE FLOOR: With all the systems available today, how accurately can we locate a point in the middle of the Pacific Ocean and another point in the middle of the Atlantic Ocean on the same coordinate system?

MR. CUNNINGHAM: Mr. Chairman, I would like to comment on that. My job now is with the Naval Oceanographic Office in the Precise Positioning Branch of the R&D Department. This is something I have been looking into very closely for the past nine months. In the area outside good Loran C coverage and over in the Pacific, where the Omega system is not operating as of

now, we do not have anything that will give any better accuracy than the navigator can take with his sextant on a star shot in the evening. VLF has been used at times, but there has not been enough monitoring to remove the diurnal effects and the ray-path propagation anomalies that are present in the VLF system. We do not have much that can be used for gravity surveys right now.

FROM THE FLOOR: The question raises a very important point. If you are to relate a position in the middle of the Pacific to a position in the middle of the Atlantic with any accuracy, the coordinate system must be defined. In a radio system, you measure lengths over the surface of the earth, in an astronomical system, the coordinates are astronomical, in a satellite system the coordinates are of another type. At the moment, it is my belief that there is no short answer to the question. If you measure the distance in wavelengths, this can be converted to miles and, if the positions are determined by the satellites, the distance in miles can be computed, but the distances will very probably not be the same.

MR. WHITTEN: Would Dr. Newton comment on this question?

DR. NEWTON: The coordinate system of the satellite system is referred to the center of mass of the earth and the spin axis of the earth. I believe this could be considered as an absolute coordinate system.

DR. WHITTEN: Can you give us the quantity we want to know? Is it a tenth of a mile?

DR. NEWTON: Do you want me to give my paper scheduled for tomorrow now?

FROM THE FLOOR: I have a question involving the first paper this afternnon on the determination of sonar beacons. I understand that no longer is the distance from the vessel to the transponder required, but just the time along the courses at which the distance is the least.

MR. ENGEL: That is correct.

FROM THE FLOOR: The problem here, I believe, is somewhat like jumping out of the frying pan into the fire, because if that is the case, you rely on direction. We assume, then, that the ocean is an even-layered body where sound velocities are parallel, but we all understand that there are some interfaces which lend to lensing of the ray, such that the rays would not be in a perpendicular plane at the point received.

MR. ENGEL: Has any determination been made of that bending? That error contribution would have to be analyzed. Hopefully, this is one of the things that I brought out in general as an error condition in the determination of the point of closest approach. There are two sources of error, two sources of noise, in the determination. One is the contribution of the navigator itself and the other is the noise in the process whereby you locate the point of closest approach. Now this is a contributor to that. It could be one of the sources of error.

MR. CAMPBELL: The oceanographers assure me they can measure average velocities, horizontal, vertical, or slant range, to an accuracy of 1 meter per second. I am a little conservative, so I have used a figure of 3 meters per second. This gave me a probable accuracy of a minimum of error of measurement of 10 meters.

FROM THE FLOOR: Yes, but this involves direction as well.

MR. CAMPBELL: No. Assuming that you use a cloverleaf maneuver, as I have described it, you do not have to get over a vertical projection of that point as long as you get within a circle of reasonable size. Actually, it could be a couple hundred meters. It is disturbing but not much of a problem.

MR. SMALET: Come back to measuring gravity, navigation, and inertial navigation. The survey business has known for a long time that you can not measure gravity on a moving platform without navigation. It is also very apparent that if you have a good inertial system, the output of it contains components of what you measure directly for gravity. Is there a possibility of using a technique of just comparing inertial velocities with noninertial velocities and dropping out the deflection values? To follow up on that, would it not then be possible to devise a good navigation system by measuring gravity and the horizontal gradients of gravity?

MR. BRADLEY: Yes, we can consider getting deflections by comparing velocities. Again this would be a relative measurement. One of the problems is getting an external reference velocity. But let us assume you could. I showed in the error diagram of few loops, for which we picked off positions and compared positions, that we can make one more integration and get velocities. You would have the same information stored in velocity and in position. So you then use this technique, provided you can get a good velocity reference. This is not very easy out in the high seas. If you use water speed, you are in error by water speed. You are also in error by the technique that I showed. As I said, we had a large signal to noise ratio. You could make a polynominal fit to position data and differentiate that to get velocity or use some radio navigational aid. There again you run into differentiation of data. However, it is possible. Does anyone want to comment on the second question?

MR. SMALET: In your method you do not have the physical measurement of gravity directly included. An analysis of what effect navigation has on gravity itself will assist you in removing some of the error sources. In other words, the

effect on gravity and the changes in the gravity itself, when you are measuring, possibly could help you in analyzing what your outputs are, and how to treat your outputs to remove some of the error sources.

MR. BRADLEY: I am not quite sure I follow that. We take the difference between the external geodetic reference and the SINS outputs. Thus we are dealing directly with an error quantity. So it really does not make any difference as to how we navigate the ship and, if we vary slightly off course, it makes no difference in determining the deflection. However, if you assume that you are determining the deflection over a course one way and you actually go another, you determine the correct deflection for the wrong position. It does not actually make an error in the deflection determination. Is that the answer to your question?

MR. SMALET: Not quite. What I had in mind was you have noise in your Loran scanner and other equipment, and you have some sort of an outlaw Schuler in your inertial system that you cannot recognize, but you are treating it as something. If you were to apply the velocity output to a gravity measurement taken simultaneously, and if some velocity output were in error, you would get a distorted gravity picture. It would help you recognize some of the things that may be removing—some of the accuracy of your technique.

MR. BRADLEY: It is another piece of information. It is a question of whether or not it is additional or redundant. The fact that you go back into your navigator one integration does not necessarily give you any new information. The fact that you have an external velocity, in addition to an external position, does give you one other piece of information. You might be able to recognize the Schuler earlier in the game because of the phase relationship with velocity information. However, the same type of error would show up in velocity as it would in position, just one integration removed. It is really questionable whether you buy anything by taking this positional piece of information. It is a point to consider.

The Navy Navigation Satellite System

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This paper is published in Space Research, VII, Proceedings of the Seventh International Space Science Symposium, Vienna, May 1966, 2 volumes, 1,500 pages, North Holland Publishing Company, Amsterdam, 1967, price $50. It describes the Navy Navigation Satellite System that is being developed by the Applied Physics Laboratory; methods of making Doppler frequency measurements; and the method of using these measurements—together with ephemeris information transmitted by satellites—to obtain a navigation fix. The paper quantitatively discusses errors encountered in using test equipment located at the Laboratory and qualitatively discusses additional errors that may be encountered in its shipboard use. Laboratory equipment yields a navigation error of 99 meters standard deviation.

Experiences With U.S. Navy's Navigation Satellite System

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The U.S. Navy navigation satellite system has been described by Guier (1966) and Newton (in press). Talwani and others (1966) have described the results obtained by this system aboard the R/V *Robert D. Conrad* during 1964-1965.

In August 1966 a satellite navigation receiver (AN/SRN-9), built at Lamont Geological Observatory from plans supplied by the U.S. Navy, was installed aboard the R/V *Vema*. A PDP-8 computer was installed aboard the ship to process the fixes. (The fixes also were later computed on the IBM 1130 at Lamont to obtain somewhat higher accuracy.) This paper describes some results obtained with the system.

Figure 1 shows the fixes obtained while R/V *Vema* was docked in Reykjavik Harbor. Fixes obtained for satellite passages during which maximum satellite elevation was less than 5° are represented by black dots. Fixes from such low-elevation satellites frequently have relatively large errors and are not considered in the following discussion. The remaining fixes are represented in figure 1 by open circles and their mean position by a cross. Half of the fixes lie within 0.07 nautical miles of the mean position. The ship's position as obtained from British Admiralty Chart No. 3201 is indicated by a star.

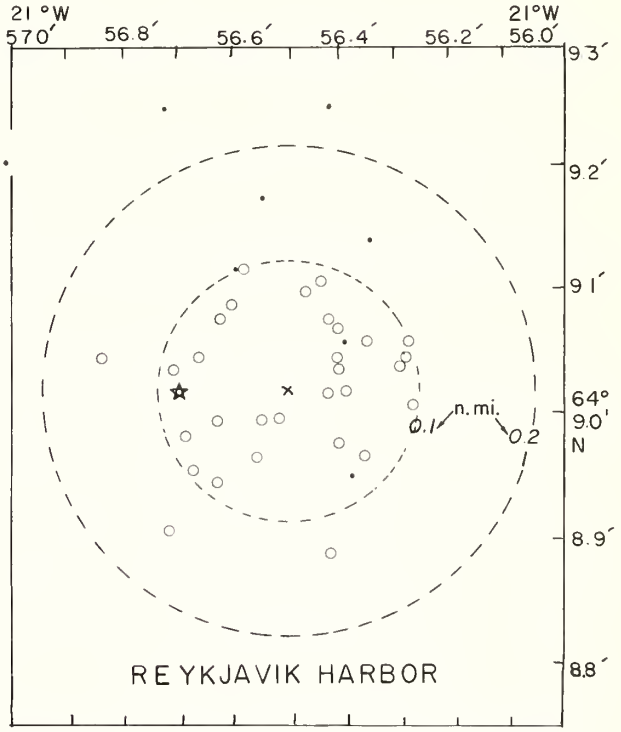

FIGURE 1.—Fixes obtained by R/V *Vema* while docked in Reykjavik Harbor.

According to Newton (in press), if two navigation receivers are used close together, the difference between the navigated position of the two antennas—after subtracting their known separation—gives a standard deviation of 13.3 meters. This is substantially better than the results of figure 1 and suggests that it would be profitable, when conducting ship surveys in limited areas close to land, to use two receivers—one at a fixed location on land and the other on board ship. The difference in the fixes obtained by the two receivers is used to determine the best position for the ship.

Figure 2 has been drawn in an attempt to correlate the errors shown in figure 1 with the direction of motion of the satellites and their position relative to the ship. The shape of each mark used in figure 2 indicates the geometry of the corresponding satellite passage. The arrowhead points in the direction of satellite motion. If the barb is drawn to the east of the shaft, the satellite was east of the station. Note that the data can be divided into four quadrants with one kind of arrowhead predominating in each quadrant. The prominent direction is indicated by the big arrowhead drawn in each quadrant. Note the large "hole" in the data northwest of the cross indicating the mean position of the fixes in figure 1. Newton

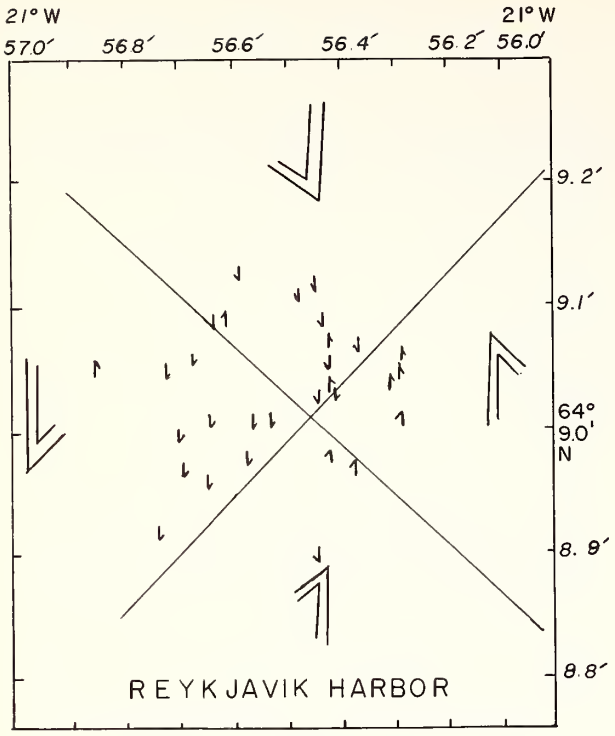

FIGURE 2.—Geometry of satellite passage showing direction of motion and position of satellite relative to ship.

(in press) believes that this behavior of the fixes is a manifestation of periodic perturbations produced by errors in the model of the gravity field used in the system. Presumably, then, a better knowledge of the gravity field will further enhance the accuracy of the navigation system.

The difference between the track of a ship at sea based on navigation satellite fixes and the dead reckoning track gives the value of surface currents. An examination of the values obtained for surface currents could give an idea of the internal accuracy of the fixes obtained by satellite navigation system.

A geophysical survey of the Reykjanes Ridge southwest of Iceland was made aboard R/V *Vema*. Nine crossings of the ridge crest are shown in figure 3. The navigation satellite fixes during each crossing are indicated. Where two fixes were within half an hour of each other the less reliable of the two fixes has been omitted. In computing the fixes the correct speed and course of the ship are required. However, in figure 3 the fixes shown employ the course as indicated by the ship's gyro and the speed as indicated by the pitlog. This can lead to errors as large as 0.2 nautical mile. The times of the fixes at either end of each crossing are also shown in figure 3. An average velocity vector for the ship for each crossing is calculated by using the times and positions of the fixes at the two ends. Also between each pair of adjacent fixes a velocity vector is computed. From this is subtracted the average velocity vector for the entire crossing and the resultant vector is plotted halfway between the two fixes. These plotted vectors, then, should indicate the varying component of the surface current for each crossing.

We note that east of the Reykjanes Ridge crest these current vectors tend to point in a southwesterly direction, while west of the crest these vectors tend to point in a northeasterly direction. Over the crest the currents are usually quite small. Slowing down or speeding up of the ship due to causes other than currents will affect the component of the deduced current vector along the track but not normal to it. (Ship's steering was by autopilot; the course actually steered varies by a degree or so about a mean value, but the deviation in course over periods of several hours cannot be ascribed to any steering errors.) The deduced current vectors have a consistent pattern and seldom exceed 0.5 knot; this must imply an accuracy in the measurement of currents of a fraction of the above value. Since these current vectors are being deduced from fixes which are about one hour apart, an internal consistency of a fraction of a nautical mile is implied for the fixes.

Acknowledgment is made to J. L. Worzel, A. C. Hubbard, and J. Dorman whose efforts contributed greatly to the setting up of the navigation receiver and computer aboard R/V *Vema*. This work was supported by the Office of Naval Research, Department of the Navy, under contracts Nonr 266 (48) and Nonr 266 (79), and by the National Science Foundation under grant GP 5392.

Lamont Geological Observatory
Contribution No. 1113

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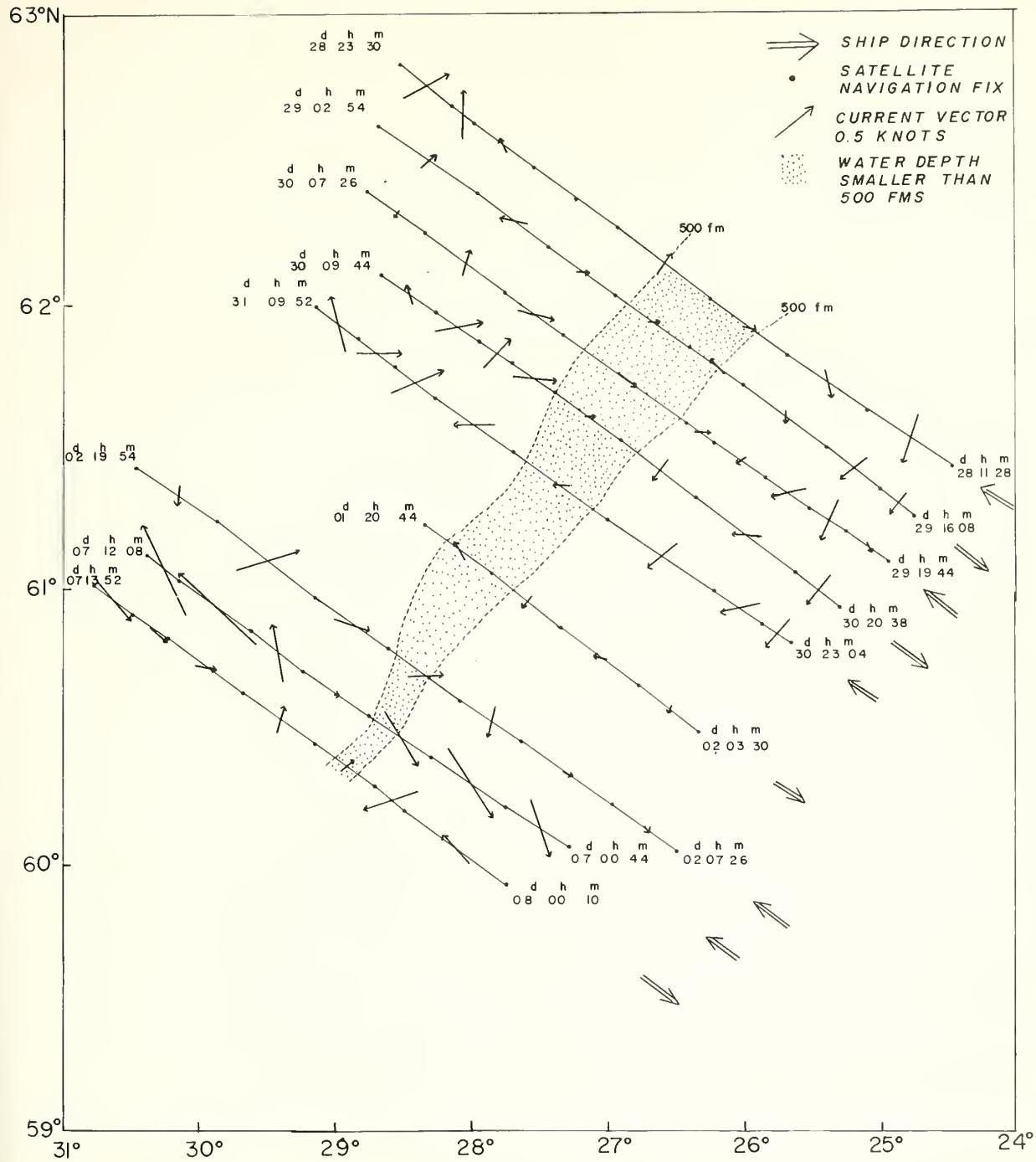

FIGURE 3.—Geophysical survey of Reykjanes Ridge by R/V *Vema* showing nine crossings of the ridge, points at which navigation satellite fixes were made during each crossing, and surface current vectors.

Secor Satellite Ranging System and its Application to Marine Geodesy

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Secor (*Se*quential *Co*llation of *R*anges) is a ranging system for measuring the ranges from one moving space point to a number of ground points in short sequences of some milliseconds. In the U.S. Army Secor version 4 to 6 ranges can be observed but up to now only the 4-range system is in operation. Range measurement is performed by phase observations.

The measuring devices are located at the ground stations and the transponder at the space point. The transponder is very small and can easily be installed in a satellite, rocket, or another space vehicle.

The measuring devices are large and heavy but can be miniaturized to the volume of a desk.

The Secor technique has been developed using the Geos satellites but the system can be installed in rockets and on ships.

Accuracy of a measured range is said to be about $\pm$ 3 m, if the influence of refraction and curvature is eliminated.

As the ranges to ground points are measured 20 times each second in which the space point is visible, many thousands of observations are available (fig. 1). From these a reasonable number of data, which provide a good geometric figuration, are chosen for the reduction. Before doing this a curve-fitting technique is applied by which all data contribute to the selected data and the influence of random errors is reduced. The measuring range lies between some 10 and several 1,000 km.

1. GEODETIC EFFICIENCY OF SECOR

Secor or Secor-type ranging systems can primarily contribute to geometric problems of geodesy: to establish and intensify networks, to connect islands and continents, to position sounding profiles, and to aid in navigation. They also can provide useful data for physical geodesy, such as the shape and the position of an orbit in a well defined equatorial system and the position of profiles over the ocean.

The accuracy of the ground points depends upon the observation error and the geometric strength of the network. As this is a purely geometric quality and the geometric figuration can be chosen arbitrarily within wide limits we should know the optimum figurations and the distribution of error in space. Therefore, I will first present results of error investigations on Secor networks which show the geodetic efficiency of this ranging device.

1.1 Resection by Ranges

The basic figure for Secor trilaterations and for ultrasonic positioning is the resection by ranges in space. With three basic points optimum accuracy is obtained if the rays are intersecting at right angles. From four basic points we get optimum accuracy in the case where the rays intersect a unit sphere around the new point in a square with the side equal to $\pi/4$. To study the error distribution in space, the point error in space, m_p, the error in the horizontal plane, m_L, and the elevation error, m_H, for a space grid with 4,000 points, have been calculated. From this we get the following information.

a. If the elevation is kept constant, all errors increase quadratically with the distance from the basic points.

b. If the horizontal position is kept constant, all errors increase quadratically with elevation.

c. All errors decrease linearly with an increase in the number of base points.

d. At an altitude equal to the small side of the basic figure, and for points inside a figure of double size, all errors are smaller than three times the observation error if 4 basic points are used and smaller than 1.5 times this error in a model with 22 basic points.

1.2 Single Transfer Net

If we determine at least 3 space points from at least 3 ground points by resection, we may regard

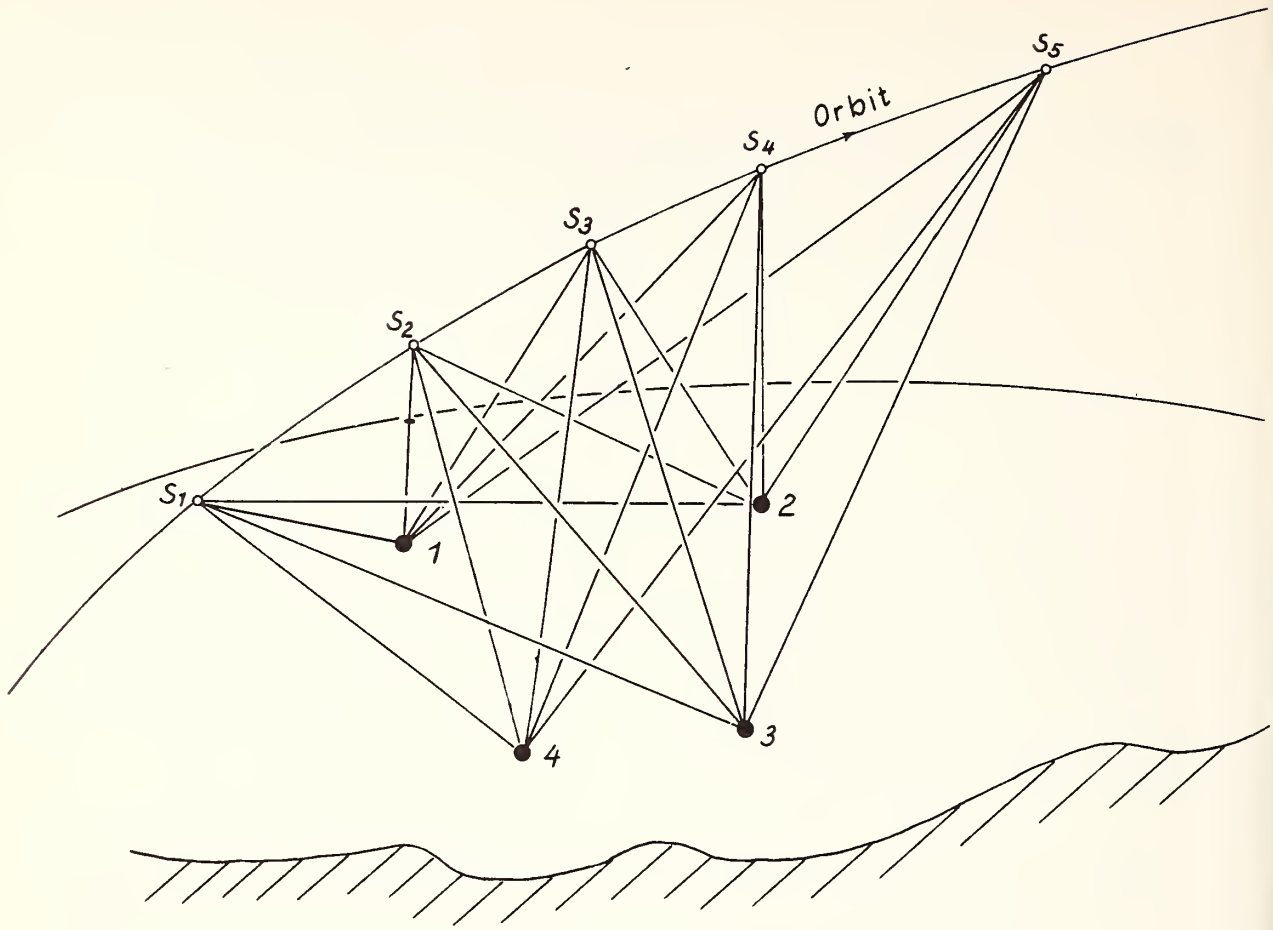


FIGURE 1

them as basic points, and can derive the position of other terrestrial points by resection again. Since we transfer the coordinate systems of the basic points with the aid of a bridge of space points we may call the whole configuration a transfer or bridging net as we do in photogrammetry. It is important to note that the number of ground points is restricted by the number of channels provided in the device, that is 4 in the U.S. Army version, while the number of space points may be chosen arbitrarily. To determine the geometric strength of such a bridging net the errors m_p, m_L, m_H have been calculated for several models in which the number of space or bridging points is different. From the results we condense the following statements.

a. The elevation error m_H, and the point error in space m_p increase quadratically with the distance from the basic points, the horizontal position error m_L increases linearly.

b. With increasing elevation, the elevation error decreases quadratically; the horizontal error increases linearly; and the point error is minimum at an altitude equal to the distance from the basic square.

c. With increasing number of space points, all errors decrease proportionally to the square root of the number of space points.

d. At a distance which equals double the side of the basic square, and for the same elevation of space points, the point error becomes about 5 times the observation error if we use 4 space points, and twice this error for 22 space points.

It is interesting that an additional measured direction to a transfer point may improve the accuracy considerably. Figure 2 shows that the influence of the elevation of space points is not significant and that all errors decrease to 40 percent if a single direction is measured to the nearest space points. In the graphs the errors

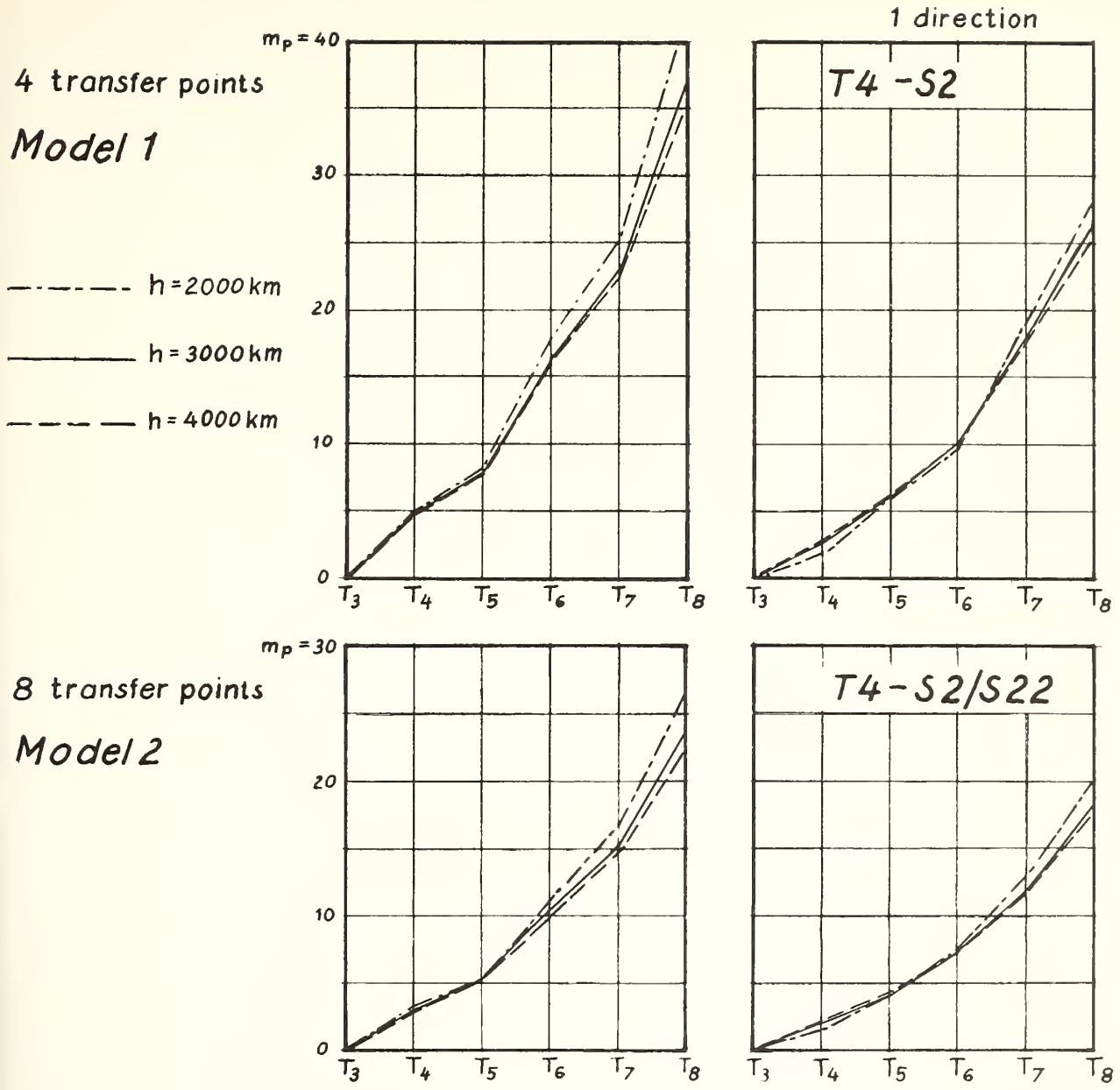


FIGURE 2a FIGURE 2b

m_j are calculated for the observation error $m_o = 1$, the corresponding value M_j for another m_o is given by $M_j = m_j m_o$.

1.3 Multiple Transfer Net

If we continue the procedure described before by joining several single transfer nets we get a multiple transfer or bridging strip. With such a strip we can connect local networks on islands and continents to a datum and condense basic networks.

The error propagation of such networks has been investigated with the aid of several spherical models. The terrestrial points are assumed to be situated on two equidistant parallel circles and the space points on the slopes of two cones which intersect them, the apices of which are in the center of the model sphere. Three different elevations for the space points were introduced (fig. 3).

In the first model 3 ground points and, alternately, 4 and 8 space points were used. The results are given in the graphs (figs. 4, 5, and 6).

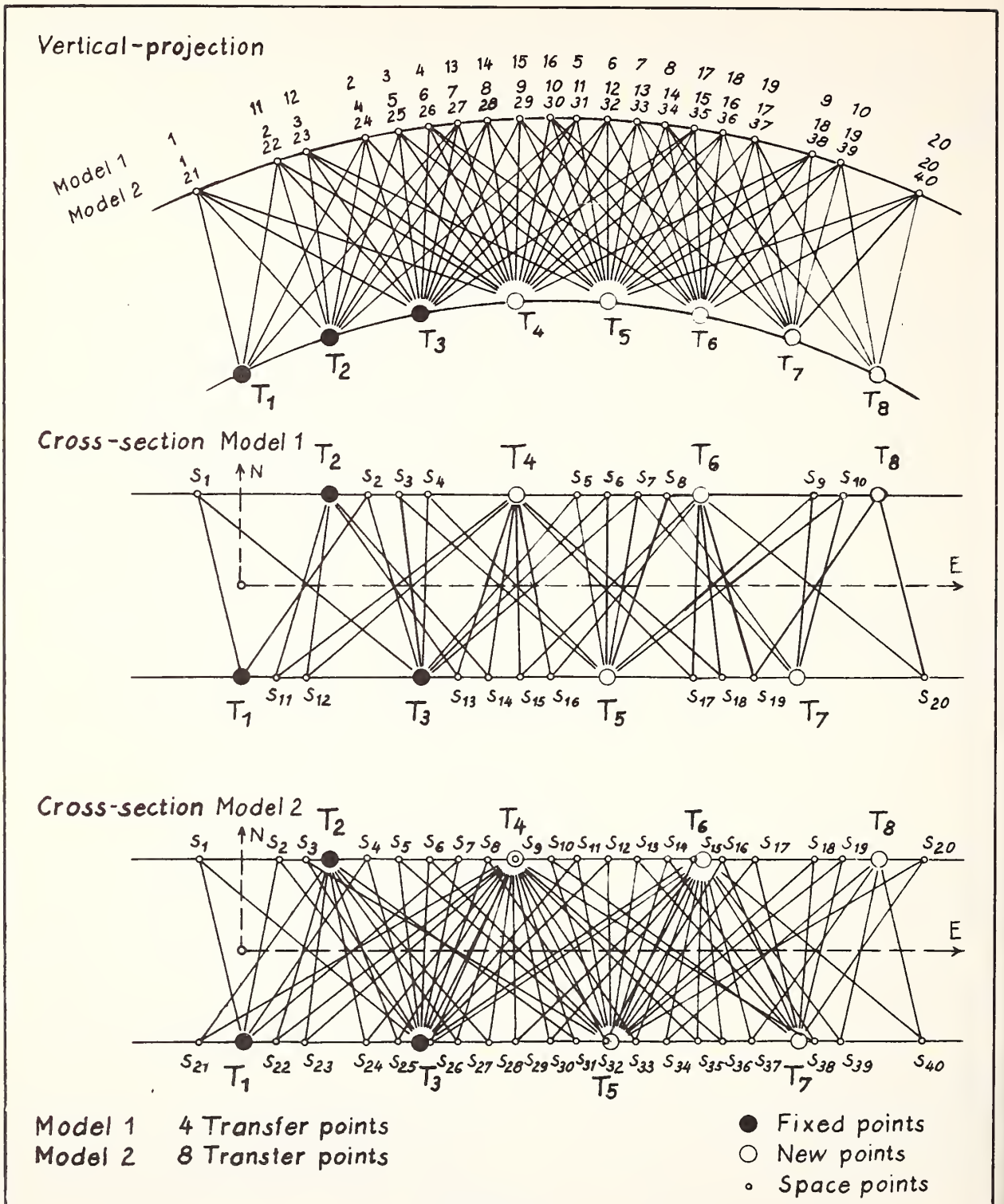
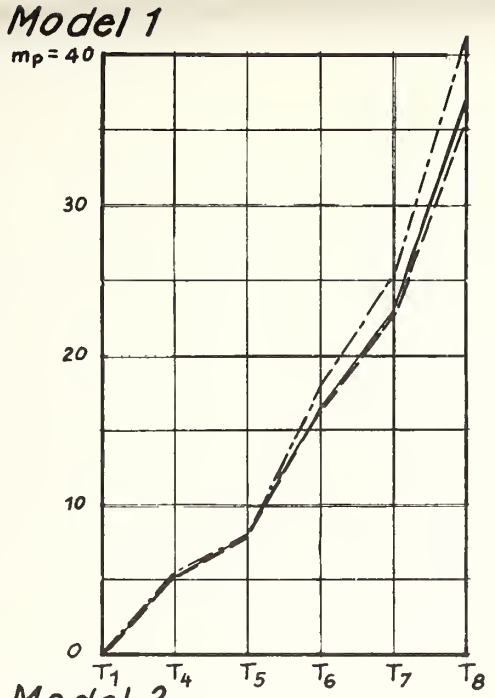

Vertical-projection
Model 1
Model 2
T1
T2
T3
T4
T5
T6
T7
T8
Cross-section Model 1
N
E
Cross-section Model 2
Model 1 4 Transfer points
Model 2 8 Transfer points
Fixed points
New points
Space points

FIGURE 3



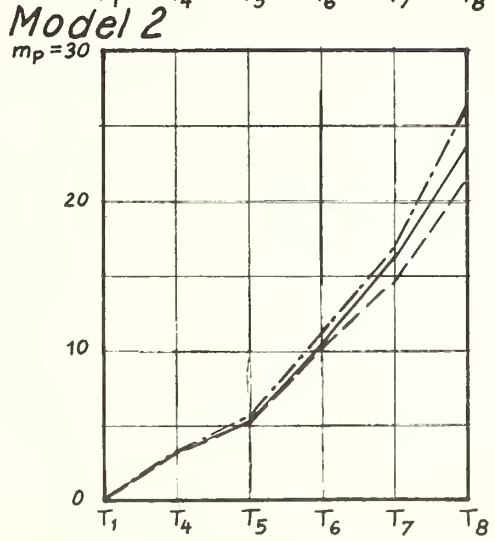
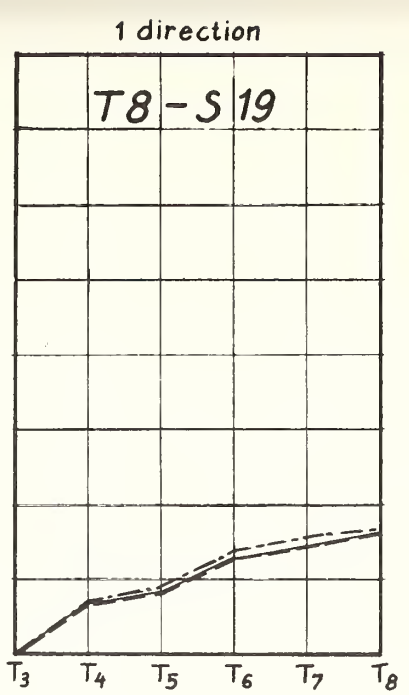


FIGURE 4



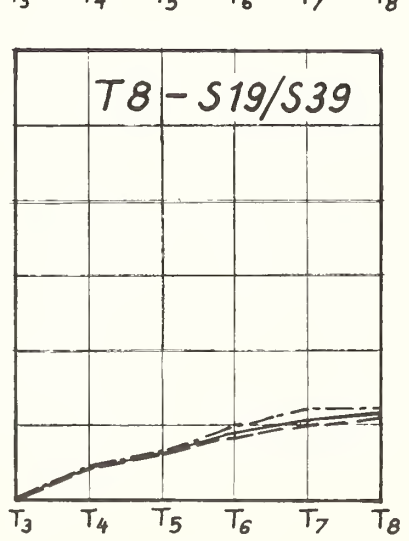
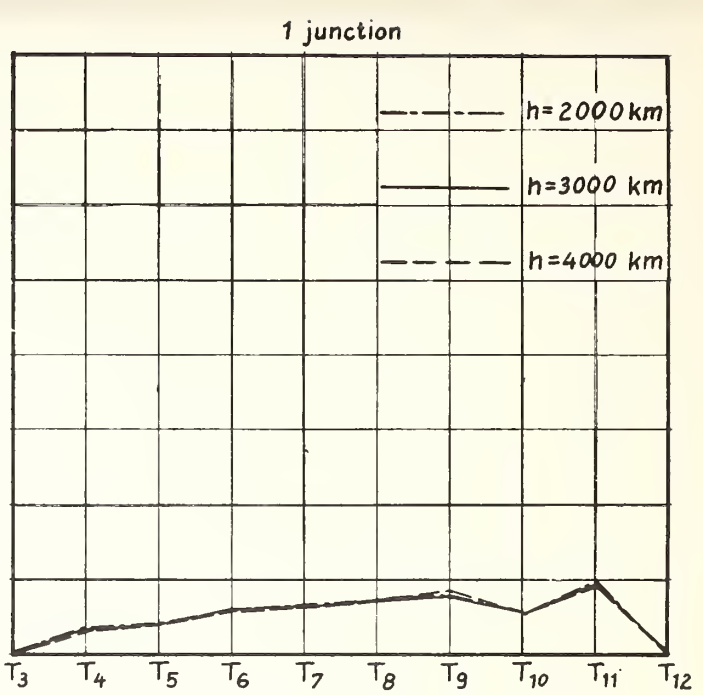


FIGURE 6



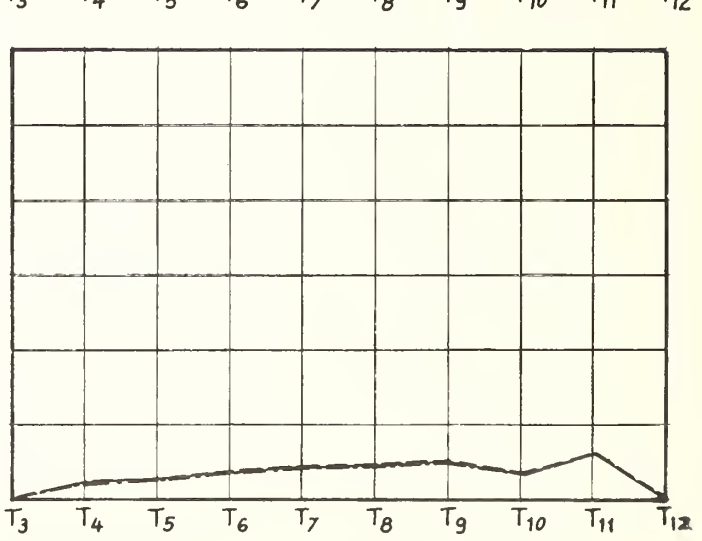


FIGURE 5

For the strip without junctions at the end (fig. 4) we conclude:

a. All errors increase quadratically with the number of transfer links.

b. If we increase the number of transfer points all errors decrease reciprocally proportional to the square root of the number of space points.

c. All errors decrease with the height of the space points.

d. After 4 transfer we get in model 1 the 20-fold observational error for the error of the space position, and in model 2 the 15-fold error.

Then a junction by given points at the end of the strip was introduced. This connected strip provides much better results. After double the number (8) of transfers to point T_{11} the point error in the same distance (point T_7) becomes 5 times, the observation error using 4 transfer points, and 4 times the error for 8 transfer points (fig. 5).

The contribution of an additional observed direction to a space point has been investigated systematically on several models. From the graphs in figure 6 we can conclude that the best result is obtained when the direction is observed from a ground point at the end of the strip to its nearest space point. By such an additional direction the errors decrease considerably to about 25 percent of the error of the free strip.

Of considerable theoretical interest are transfer nets which circle the globe. The graphs in figure 7 show the results of test calculations with 4 and, alternatively, 8 transfer points. Therefrom we conclude:

a. All errors decrease with the elevation of space points.

b. All errors decrease approximately with the square root of the number of transfer points.

c. The total error and the horizontal position error both reach their maximum values opposite to the area from which the strip started.

d. The elevation error has 2 maxima with a phase of 90 and 270 degrees from the basic.

e. With a realistic elevation of 4,000 km, the total error is 40 times larger than the observational error when 4 transfer points are used, and 25 times for 8 transfer points.

1.4 Figurations for Determining Basic Figures

a. By ranges only.—In the networks described earlier we assumed that 3 or 4 ground points were known. Even if we want to determine the relative positions of additional points only, 3 ranges between three ground points must be known. This fact imposes a restriction on the use of such networks.

We can avoid this problem by using a configuration with 4 (or 6) ground points and 6 (or 4) spatial transfer points, assuming that all ranges between ground points and all space points are observed. By adding additional transfer points from which all ranges to all ground stations have been observed, we get a solution by adjusting the now overdetermined problem. We must, however, avoid points on an orbital surface. This condition occurs if all points are placed on a surface of 2nd order, or if the ground points and/or the space points, are arranged in a plane. We can combine such a configuration of the basic points if only the relative positions are of interest.

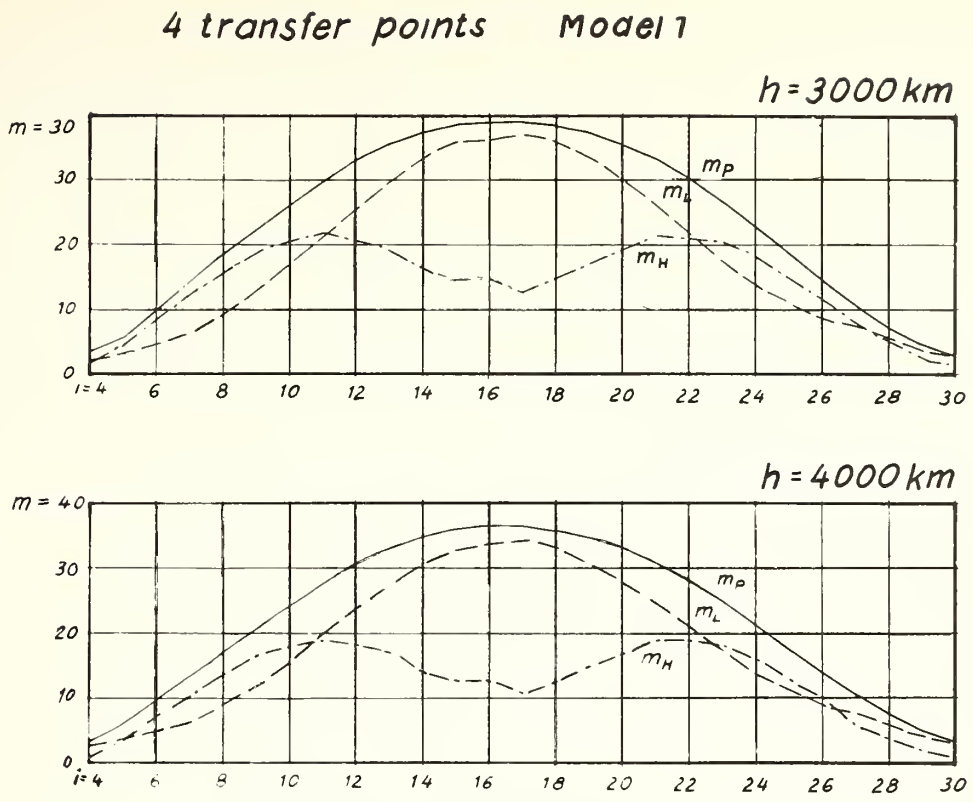
b. By ranges and directions.—Combining range measurements with optical observations of spatial directions we obtain further networks for determining the primary figures.

If we determine the spatial directions between 4 ground points by the well-known *Väisälä* procedure each quadruple of ranges to a space target provides the scale in such a figure. Using more space points, we get overdeterminations and the accuracy will be increased by adjustment.

A vertical baseline can be measured with Secor-ranging systems and Doppler devices if both are installed in an approximately vertically launched rocket. The rocket, in addition, shall be equipped with as many as possible timed flashes which are photographed against the star background from a number of basic stations. From Secor and Doppler we can compute the vertical baseline between any two flashes. From simultaneously executed optical measurements (without time) we obtain the relative position of the points of the base figure. Its spatial orientation is known except for a rotation around the direction of the earth's axis. If the time of the output of flashes also is observed, full orientation is provided. The use of 2 different devices for determining the baseline seems to be especially convenient from a system standpoint.

2. SPACE TRILATERATION OVER THE OCEAN

The observation of geometric data, such as angles, directions, and ranges, is more complicated in nautical geodesy than on land. On the sea bottom itself, no observations can be performed up to now. The surface on which the measuring devices can be placed is moving. Between the points of observation and the targets there are two mediums, the ocean and the atmosphere. In the ocean, light and microwave propagations are weak.


4 transfer points Model 1
h = 3000 km
m = 30
30
20
10
0
i = 4
6
8
10
12
14
16
18
20
22
24
26
28
30
m_P
m_L
m_H
h = 4000 km
m = 40
30
20
10
0
i = 4
6
8
10
12
14
16
18
20
22
24
26
28
30
m_P
m_L
m_H

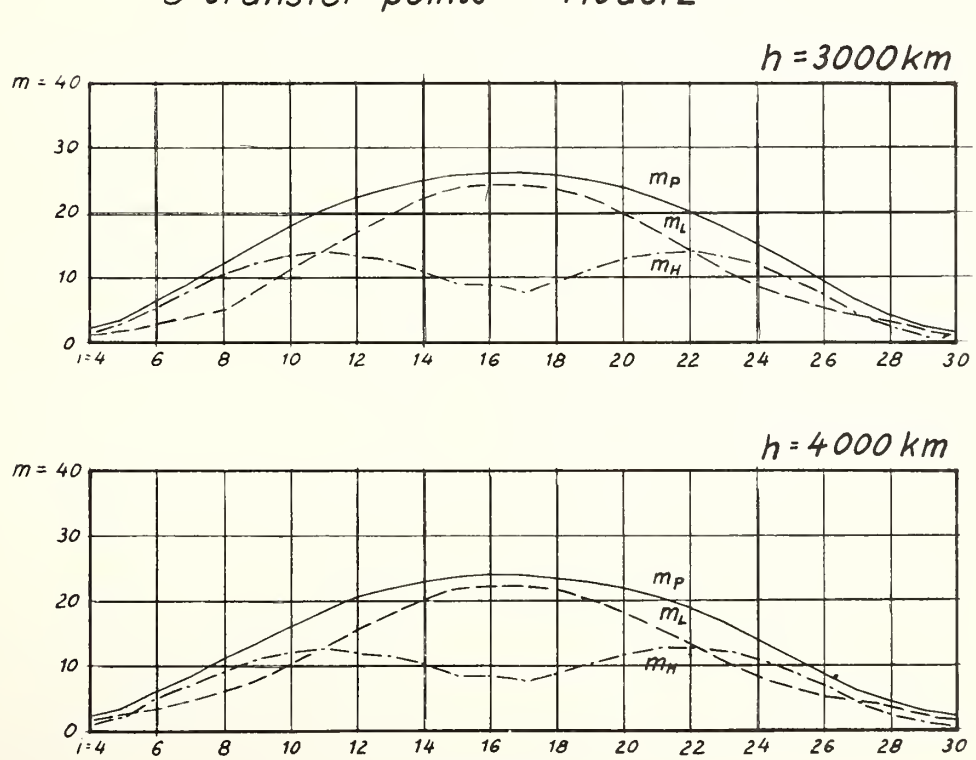

8 transfer points Model 2
h = 3000 km
m = 40
30
20
10
0
i = 4
6
8
10
12
14
16
18
20
22
24
26
28
30
m_P
m_L
m_H
h = 4000 km
m = 40
30
20
10
0
i = 4
6
8
10
12
14
16
18
20
22
24
26
28
30
m_P
m_L
m_H

FIGURE 7

On the other hand, we know that the surface of the quiet ocean is a good approximation for the geoid. Because the tides are well known, we can replace the surface in a limited-operation area by a sphere or an ellipsoid and assume that all heights are known.

Contrary to angle measurements and optical methods using star photography, range observations are very little affected by movements of the observation point. Trilaterations, therefore, are well suited to determine fixed points in ocean areas.

This can be done by networks which are spread over the surface of the sea or by spatial networks. Surface networks can be established with the aid of phase difference observations. Nevertheless, for several reasons, they cannot provide the required accuracy and are restricted in range.

Spatial trilateration networks can be established from fixed points on continents or islands without any additional assumptions. But we may also use the condition that all observation points on the ocean are situated on a known surface making proper reductions for tidal movements. With this consideration, we are reinforcing the geometric strength of the network. In any case we must, however, establish permanent markers on the bottom of the ocean.

2.1 Establishment of Markers

Fixed points must be established on the bottom of the sea. Since at present only ultrasonic distance observations can be used in water over long ranges, we must establish at least 3 fixed points on the sea bottom; these should be placed in an optimum figuration. For control, a 4th station is desirable. The observation point on the surface can be determined by the ranges to the markers. To one of them, which we shall call a master station, all observations in Secor trilateration shall be reduced and its coordinates shall be determined by the adjustment.

Two steps make it possible to refer Secor ranges from the surface point to the master station on the sea bottom.

a. First establish 2 additional eccentric stations (E_1 and E_2 of figure 8a) on the surface during the trilateration operation. The distances between them and the surface reference station (W) are observed simultaneously with the ultrasonic ranging to the markers on the sea bottom. This can be accomplished by microwave distance measurements. From these range observations the geometric shape of the 3 centering pyramids W, E_1, E_2 and T_i (i = 1, 2, 3) are known. If we observe, in addition, the azimuth of one side of the surface triangle (W, E_1, E_2) and know an approximate value for the latitude and longitude of W we can orient the pyramids in the equatorial system used in space trilateration. Then, we can calculate the angles between all measured ranges and refer the ranges to the master station on the sea bottom.

b. Second, we determine the distances between the markers T_1, T_2, and T_3 (fig. 8b) by ultrasonic line crossing, calculate their elevation angles from soundings, and determine the azimuths from the azimuth of the crossing line on the surface. From these data and the ultrasonic ranges from the surface station W to the markers T_1, T_2, T_3 the shape and the position of the centering pyramid (W, T_1, T_2, T_3) in the horizontal system through W is known. With the aid of an approximate value for the latitude and longitude of W, the transformation from the horizontal system into the equatorial system of Secor trilateration can be performed, and the angles between Secor and ultrasonic ranges and therefrom the distances from the satellite to the master station on the sea bottom can be calculated.

2.2 Determination of Geodetic Reference Points Near the Coastline

Up to a distance of 1,500 km from the coast, fixed points can be established by the single transfer procedure described in section 1.2. We start from 3 or 4 known points on the coastline, determine a number, $n \geq 3$, of spatial points, and derive by range resections and a centering procedure (see Section 2.1) the fixed point on the sea bottom.

For many purposes, a much simpler procedure will be sufficient. We assume the surface of the ocean in the surveying area to be a sphere, the radius and the position of which are known from basic triangulations on the neighboring continents. In this case, range observations to only 2 points of one orbit will suffice to determine the desired position; the 3rd range being the radius of the oscillating sphere and the 3rd known point being its center. Each range provides a position line. The redundant observations, available by this routine, increase the accuracy of the determinations.

2.3 Determination of Geodetic Reference Points in the Open Sea

Multiple transfer nets can be used for this task. But junctions at both ends must be provided. These may be coordinates, directions to space points, base lines, or directions between junction points even without coordinates.

Again the geometry becomes stronger if the elevations of the "ground" points can be assumed to be known. In this case the point error equals about the horizontal position error.

In some cases, it may be possible to use a short arc solution in which the ephemerides of the satellite over the working area are known. Such infor-

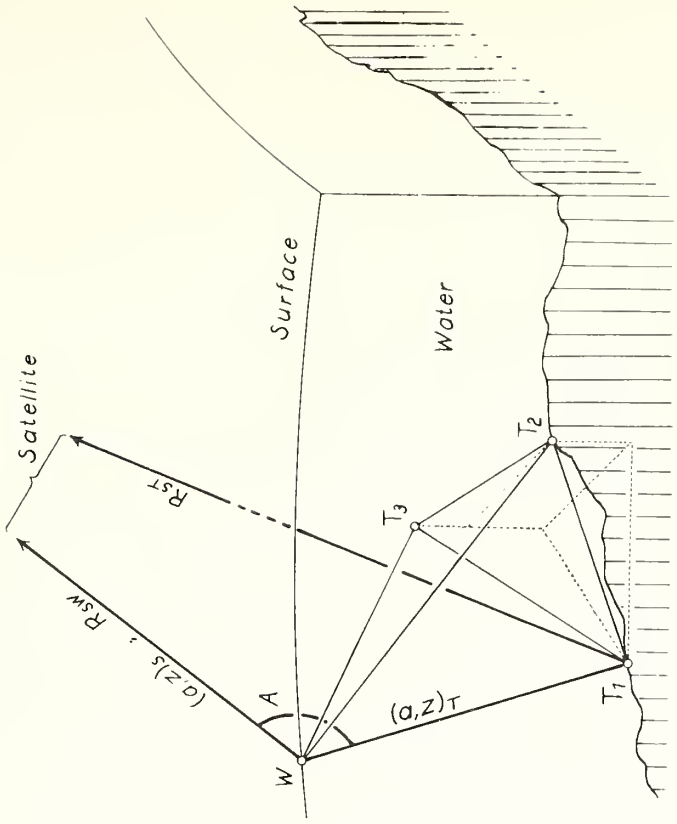


FIGURE 8a

FIGURE 8b

mation can be derived from observations on continents or fixed points on the sea. In this case, we must measure the time of observations very accurately. The orbit provides fixed-space points as a function of time. From these points the position on the ocean can be derived in accordance with the methods described before. This procedure seems especially suited to intensify trilaterations in which the fixed points are available from a basic trilateration.

3. NAVIGATION

Ranging systems may also be used for navigation. Installed in polar satellites they can provide positions by long arc solutions. That means the parameters of the orbit have to be determined by satellite tracking from known stations. The corresponding ephemeris can be stored in the satellite. Positioning of a ship consists in observing at least 2 ranges to the satellite including the time of observation. The time can be transmitted by the satellite. From these data the positions of the satellite and of the ship can be calculated. In the ideal case the satellite would transmit its own position when interrogated.

This concept corresponds to the well-proven Doppler navigation system. However, because of the strong geometry of range networks, their results will probably be more accurate than results based on range differences. Even if the accuracy of range-difference measurements is n-times higher than the corresponding accuracy of range measurements the final results will have only the same accuracy as soon as the range is n-times the length of the difference. In addition, the geometry associated with difference measurements is typically weaker than for ranging systems. Therefore, ranging systems should provide better results when compared with systems using differences of ranges. But it is a matter of economy if these strictly geometric considerations are valid for practice.

FINAL REMARKS

The Secor ranging system or a Secor-like system, seem to be a very useful tool for marine geodesy. Its accuracy is sufficient to establish basic geodetic networks on the oceans and it offers some advantages as compared with optical and Doppler systems. The use of Secor for the manifold tasks of marine geodesy can be recommended, and the agencies using Secor systems on continents should be invited to test the system on the oceans.

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Photogrammetric Ocean Survey Equipment

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1.0 INTRODUCTION

The Air Force Eastern Test Range must provide the geodetic position of missile impacts for guidance and reentry evaluation testing. Impact location can be determined relative to underwater hydrophones or transponders, hereafter referred to as "beacons," by time-correlated distance measurements. The true geodetic position of these beacons must be applied to this relative data to obtain the geodetic position of impact.

A calibration ship is used to locate the beacons initially. If the geodetic position of the ship is known, the geodetic position of the beacons can be determined. Once the position of the beacon is known, it can be used on a real-time, all-weather basis for missile impact and ship positioning purposes.

The Photogrammetric Ocean Survey Equipment (POSE) Program was initiated at the Eastern Test Range (ETR) to help solve the ship positioning problem. Stellar-oriented cameras are used at the ETR for accurate geodetic positioning of land-based tracking instruments. This technique involves simultaneous observation of a satellite with several land-based cameras. If the geodetic position of two or more of these cameras are known, the positions of the other cameras in the network can be determined by triangulation.

The POSE system consists of a gyrostabilized, stellar-oriented camera, with associated timing equipment, mounted aboard a ship. The shipboard camera is treated as a station of unknown position in the triangulation network. The sounding measurements obtained from the ship are applied to the triangulated position of the shipboard camera to fix the geodetic position of the bottom beacons.

In addition to missile impact location, accurately positioned beacons will permit geodetic positioning of instrumented ships used to track missiles, satellites, and space vehicles. They will also serve as reference points to calibrate navigation equipment and can be used for ocean bottom surveys. If extended across oceans, they will permit intracontinental geodetic ties.

2.0 CONCEPTS

The objective of the POSE program is to develop a stellar-oriented camera which can be mounted on a ship. The camera must be sufficiently stabilized to permit pointing in a selected direction. The shipboard camera and several land-based cameras simultaneously observe a light source on or reflected light from a satellite against a star background. The opening and closing of the camera shutter results in gaps and discrete points in the recorded star image trace. These gaps or points are used to determine the camera orientation. During the shutter open period, light energy from the satellite is also recorded by the ship-mounted and land-based cameras.

The position of a given data point is determined by simultaneous triangulation from land-based cameras. Using this position data, the image coordinates of the point as observed from the ship and the known orientation of the shipboard camera, the ship's position is computed. The ship's position is then time correlated with the ship's records to determine the geodetic position of the fixed beacons. The need for land-based cameras can be eliminated when sufficiently accurate orbital elements of the target satellite are available.

The fundamental techniques of spatial triangulation are used to determine the position of the shipboard camera as a function of time. Only the intervisible mode of operation is used presently at the ETR. Ship positions are computed using revised mathematical techniques formulated originally at the ETR by D. Brown [1957, 1960].

This report will stress problems related to photographic recording of high quality star and target images and their relation to equipment design. Image quality is of particular importance for it, along with proper timing, determines the ultimate accuracy of ship positioning.

The effects of random, steady, and enforced drift of a shipboard gyrostabilized camera on photographic imagery must be considered. Random drift is defined as the residual rotation about the platform axes due to imperfect response of the gyroscope, gyroscope sensors, and servoloops to ship motion. This drift approximates simple harmonic motion and is evidenced by the sinusoidal appearance of the photographic image traces on the camera plate. The period of this random drift approximates the period of ship roll, pitch, and yaw.

Steady drift results from gradual changes in the servosystem and precession of the gyroscopes. Steady drift, unlike random drift, is cumulative with time, but it is small and normally has only minor effect on imagery.

Enforced drift results from purposely applying torque to the platform gimbals so that the optical axis of the ballistic camera sweeps through a given angle at a preprogrammed rate. A platform perfectly stabilized in an inertial mode will build up stellar images at the same place on the photographic plate, as is the case with a sidereally driven telescope. In this case enforced drift is not required. Perfect stability is not achievable; consequently the images will appear to wander on the plate as shown in figure 1, unless they are spread out by enforcing platform drift. Figure 2 shows the image traces

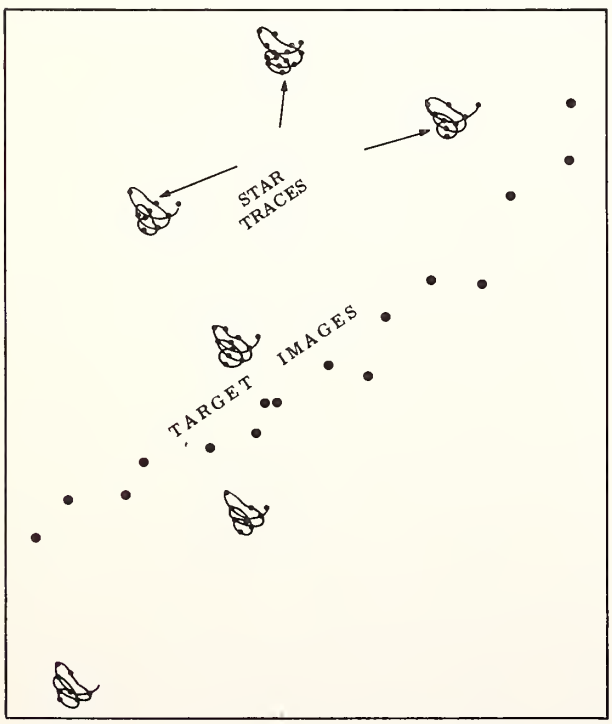

FIGURE 1.—Gyro-camera images—poor stabilization and no enforced drift.

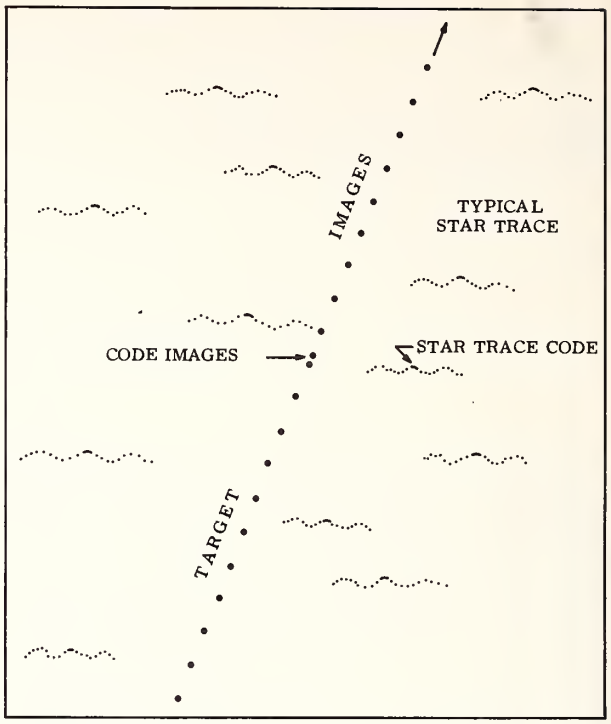

FIGURE 2.—Gyro-camera images—good stabilization and enforced drift.

obtained when drift is enforced and moderate amounts of random and steady drifts are present.

A condition that would permit adequate recording of star and satellite images would be to orient the gyro-camera pitch axis transverse to the orbital plane and then enforce pitch drift in the direction of satellite motion. Satellite motion in this case is much greater than platform drift. The apparent satellite motion will be least when random, steady, and enforced drift motions are in the same direction as satellite motion. A polar orbiting satellite traveling from south to north will be assumed. The gyro-camera pitch axis will be oriented east-west and pitch drift will be enforced from south to north. Under these conditions the gyro-camera will be compensating for earth rotation in the east-west direction (due to inertial pointing) except for random and steady drift effects.

Platform drift motions in this case are essentially changes in elevation angle when short period observations are made near zenith. Since the star is fixed inertially, its image will appear to move from north to south on the plate (see fig. 3). Time variant positions of the star and target images can be computed to determine their velocities at the photographic scale. These velocities can then be incorporated into photometric equations to determine the effects of platform, motion, as well as camera and emulsion parameters on image recording.

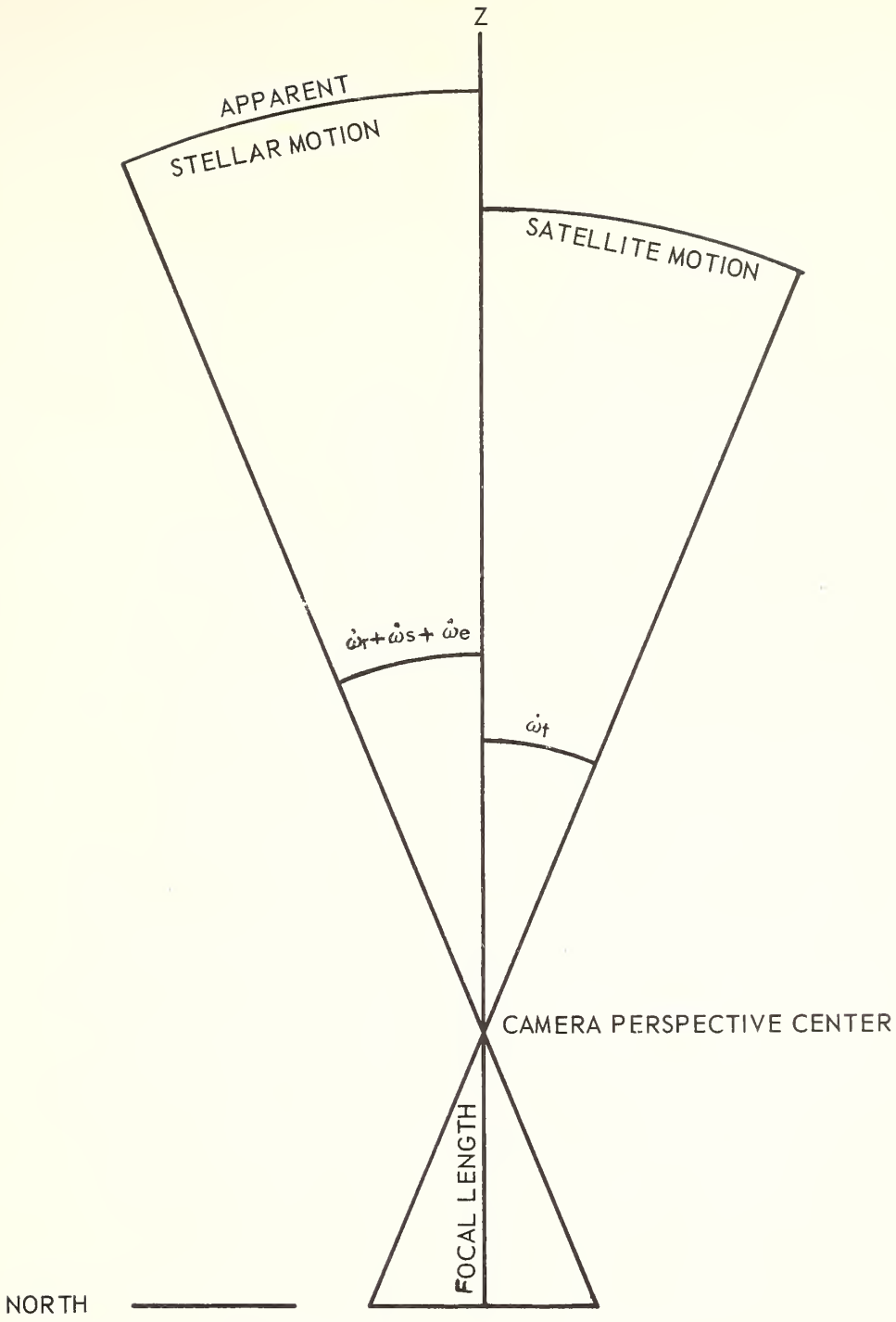

FIGURE 3.—Apparent star and satellite motions.

A mathematical determination of image characteristics under varying conditions of ship velocity, earth rotation, platform drift, satellite orbit, and other factors encountered during test operations is given in Jury [1965]. Figure 4 shows the general relationship of ship, camera, and satellite during a test.

The time variant star $(\overline{x}_S, \overline{y}_S)$ and target $(\overline{x}_T, \overline{y}_T)$ optical image coordinates can be de-

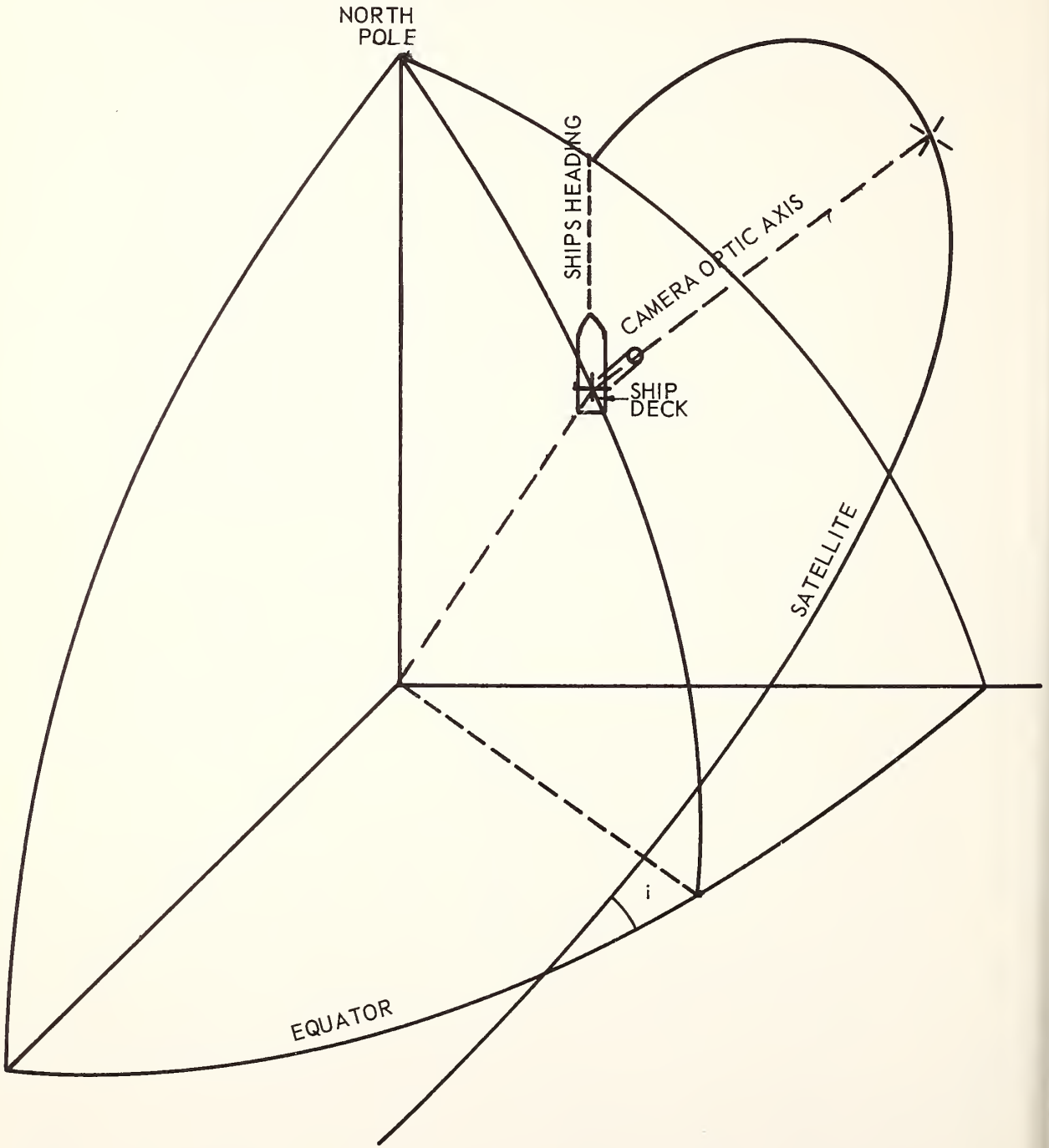

FIGURE 4.—Ship, camera, and satellite relationships.

termined from displacement equations defined in Jury [1965]. If image motion is uniform, the optical image velocity v_S of the star and v_T of the satellite can be approximated to sufficient accuracy from

$$v_S = \left[(\Delta \bar{x}_S)^2 + (\Delta \bar{y}_S)^2 \right]^{\frac{1}{2}} \Big/ t \qquad (2.1)$$

$$v_T = \left[(\Delta \bar{x}_T)^2 + (\Delta \bar{y}_T)^2 \right]^{\frac{1}{2}} \Big/ t \qquad (2.2)$$

where

t = time from first to last star or target points.

The optical image length of the star and target at the photographic scale can be found from

$$IL_S = v_S \times \Delta t \qquad (2.3)$$

$$IL_T = v_T \times \Delta t \qquad (2.4)$$

where

Δt = camera exposure period.

The photographic image formed is dependent not only on the characteristics of the optical image, but also on the photographic emulsion.

Empirical equations formulated in Brown [1960] and Sixby *et al.* [1962] are helpful for determining image sizes. For Kodak 103F emulsion developed for 8 minutes in D-19 at 68 °F., photographic images of stars of spectral class AO can be described in the empirical relation:

$$F_d \Delta t = \frac{\pi d^2}{4} (1.9 + 0.00012\, d^2) \times 10^{-14} \qquad (2.5)$$

where

F_d = luminous flux (lumens) required to produce a photographic image of diameter d

d = image diameter (microns)

Δt = exposure time (seconds).

F_d also depends on the magnitude of the source, atmospheric transmission, light transmission of the optical system, and aperture of the lens. Thus

$$F_d = E_m T_a T_l A$$

where

E_m = illuminance of a star of visual magnitude m at the top of the atmosphere = $(2.43)(2.51)^{-m} \times 10^{-6}$ (lumens/m^2)

T_a = atmospheric transmission

T_l = transmission of the optical system

A = lens area = $\frac{\pi D^2}{4}$

D = objective lens diameter (meters)

T_a can be specified as zenithal attenuation of starlight in terms of apparent increase Δm of the visual magnitude. For off-zenith conditions, this becomes Δm sec Z where Z is the zenith distance of the star and $\Delta m = 0.26$ for a clear atmosphere. Thus

$$F_d = 2.43 e^{-0.92(m + \Delta m \sec Z)} \times 10^{-6}\, T_l \frac{\pi D^2}{4} \qquad (2.6)$$

Equation (2.5) can be used to compute the image size of an object which maintains its same relative position in the angular field of view of the camera. In this case exposure is building up an image at the same point on the plate. If, on the other hand, the recorded object moves rapidly across the plate, the trail width produced will depend on the magnitude and velocity of the object and will be nearly independent of the duration of the exposure. Sixby *et al.* [1962] show that time integration of an emulsion illuminance function yields:

$$F \approx 4.8 \times 10^{-18} v\, a \sqrt{a^2 + 4000} \left(a + \sqrt{a^2 + 4000} \right) \qquad (2.7)$$

where

F = flux (in lumens)

v = image velocity (micron/sec)

$2a$ = image trail width (microns)

The flux required to form an image of trail width $2a$ can be approximated with (2.7) by introducing the image velocity v obtained from the displacement equations and any selected value of a. The flux values thus obtained, along with selected camera parameters, can be substituted into (2.6) to approximate the stellar magnitudes that can be recorded at a given elevation angle. For rapidly moving images, the image length will be essentially a function of image velocity

and exposure period. When platform rotations approach inertial conditions (2.5) can be used to approximate stellar image size, exposure period, and other parameters. The camera would have to approach the angular velocity of the satellite before (2.5) can be applied to calculate the corresponding target parameters.

Evaluation of these and other photometric equations is continuing in an effort to find the most suitable expressions for gyrocamera image simulation. The trail width of a stellar or satellite image can be approximated quite accurately if the input parameters are well defined. The length of the trail is a function of image velocity during the exposure period and emulsion characteristics.

The angular field and pointing direction of a camera of given focal length and format size will determine the number of potential stellar images that can be recorded. Star charts and catalogues can be used to determine the quantity, class, and magnitude of stars that should appear in the field of view. Let it be assumed that nearly circular images between 30 and 100 microns in diameter are desired for data reduction purposes. The number of stars within this range that will be recorded can be determined by introducing the desired variables in the appropriate displacement and photometric equations. The conditions which will permit the simultaneous recording of both star and target images of suitable quantity, size, shape, and spacing can also be determined. The degree of stabilization required to obtain the images needed can be found by changing the variables. The most desirable camera focal length, aperture, angular field, exposure period, and exposure interval can likewise be defined.

3.0 TESTING AND EQUIPMENT DESIGN

Joint tests using a U.S. Naval Oceanographic Office stable platform and AFETR camera equipment were conducted earlier in the POSE Program [Vance, 1962]. This two-axis, one-gyro mount permitted stabilization in roll and pitch, but not in azimuth. Stability of the platform was about 1 to 2 arc minutes. The platform was modified to permit ±3° induced drift at varying rates in both roll and pitch. This permitted a gradual rotation of the camera optic axis during operations.

Both 210 and 300mm focal length cameras were used on the platform. A driver unit operated the camera shutter with a preprogrammed, time correlated tone signal such that discreet star and target images were spread across the photographic plate.

These tests showed that drift rate, exposure time, exposure interval, and aperture must be closely controlled to obtain maximum data on the photographic plate [Jury, 1963]. If the drift rate is too great, the stars are swept across the emulsion too rapidly and only six to eight very bright stars are photographed. Several stars are desired to compute a least squares solution of camera orientation against time. If the drift rate is too slow, the images tend to overlap or become too large. If the exposure time is extended, the images become elongated and too large, making comparator measurement difficult. When the exposure interval is too short, the images tend to overlap. Long exposure intervals result in less data and reduce the accuracy of computation. Poor system balance causes slurring of the images. Thus, best results require almost perfect combination of all factors.

Because of imperfect roll, pitch, and yaw compensation, residual motions of the camera occurred, giving interrupted stellar traces a sine wave appearance (see figure 4). The amplitude and frequency of these sine wave traces depended on the nature of the ship roll, pitch, and yaw, the quality of stable platform compensation, and the degree to which the system was balanced. The wave length depended primarily on the induced drift rate. With ideal roll, pitch, and yaw compensation, the interrupted star traces appear as nearly straight lines. Quality data, however, can be extracted from the sinusoidal traces [French *et al.*, 1964].

Test results with the USNOO stable platform, and subsequent studies indicated that a steadier platform with three-axis stabilization would produce better data [Conrod, 1963]. Such a platform was obtained. It is about six feet in diameter and six feet high. Its three-axis, three-gyro platform has a steadiness of approximately eight arc secs over a period of 3 min, the normal observing period for gyrocamera ship positioning. For platform stabilization it has 30 ft. lb. dc torquers, with limits of ±12° in pitch and roll and ±360° in azimuth. Induced drift about all three axes is possible. The platform will stabilize a load of up to 2,000 lb. A high quality 600 mm focal length F2 camera weighing about 1,500 lbs. was placed on the mount. Excellent stellar images are formed using a platform drift rate of 90 arc/secs/sec, exposure time of 200 milliseconds, and an exposure interval of 3 secs.

Timing to actuate the shutter blades is provided by a time code generator which contains a stable oscillator that is synchronized to WWV and Loran-C transmissions. Shutter blade actions are monitored by magnetic "pick-ups" which provide a signal that is recorded against time on magnetic tape. Timing accuracies of better than 0.5 millisec are attained.

The system has been operated aboard ship at sea in a preliminary test mode for positioning purposes. Echo I and II were used as targets. The ship's position was determined with the POSE

system and separately with Lorac-B equipment. Three separate solutions were obtained where either three or four land-based cameras were used in the solution. The positions thus obtained differed by approximately 57 feet in latitude and 192 feet in longitude. These tests, although interesting, are not conclusive because the Lorac-B system was not an adequate standard. Shutter vibration of land-based cameras also contributed considerable error to the solution.

These difficulties have been remedied and additional tests completed. Active satellite Geos lA, as well as passive satellites Pageos, Echo I, and Echo II were observed. Reduction of this data is in progress. These tests are expected to produce ship position accuracies of better than 100 ft. linear standard error.

Computer data relating to image formation are also being studied to determine optimum platform, camera, and timing system design. Completion of these studies is expected to result in definitive design of a self-contained, compact, portable system that can be used aboard any ship of reasonable size.

4.0 CONCLUSIONS

The techniques outlined in this report can be used to describe image quantity, size, shape, and spacing that will be recorded under varying dynamic conditions. The equations used will also accommodate ship roll, pitch, and yaw values directly and thus will permit evaluation of image behavior on the photographic plate of a rigidly mounted camera. The simultaneous solution of the equations in reverse order could prove to be an excellent means of accurately defining ship or stable platform rotation values.

For long-term oceanographic use, a passive bottom reference marker would be most useful, since it would be essentially maintenance free. If necessary, a small, nearby nuclear-powered transponder could be used for basic acquisition of the passive target. This arrangement would reduce beacon energy requirements and extend its lifetime.

Ultimately one can expect that accurate ocean bottom maps will become as common as land maps. This will take a lot of control surveys and considerable time, since nearly three-fourths of the earth's surface area is involved. A means for obtaining an ocean bottom control network during normal oceanographic research expeditions appears most desirable.

It is believed that a compact, self-contained POSE system aboard an oceanographic research vessel could do much toward providing such a control network. The shipboard unit would be used in conjunction with five land-based cameras appropriately located at points known to have little cloud cover. The geometry of these stations could be preselected to insure a wide area of ship coverage. The Pageos satellite at an altitude of approximately 2,300 nm offers very good geometry. Excellent Pageos images have been recorded with the POSE system at the ETR. An active satellite at the same altitude, with sufficiently bright flashes, could provide even greater accuracy since camera-to-camera time synchronization is achieved when the flash occurs.

Since optical systems have weather limitations, sufficient observing time must be allowed at each control point. The great advantage of the optical approach is the availability of an excellent stellar standard on each data plate.

The techniques described in this report can also be applied to aircraft, missile, or satellite-borne cameras. Certain refinements, however, will be required.

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Session V Panel Discussion

R. R. NEWTON, *Chairman* (Applied Physics Laboratory, The John Hopkins University, Silver Spring Md.)

DR. HAMMER: Dr. Newton, in your paper you described the accuracy of the system as approximating ±5 meters and in the tests at sea results of ±100 meters were obtained. How do you account for the gap?

DR. NEWTON: The gap is the inability to calculate the position of the satellite because of not knowing enough about the gravity field of the earth. In other words, at the present time the ability to calculate the position of the satellite for an interval is limited to approximately 50 to 75 meters. The 100 meters is the overall limit to which the position of the satellite can be computed. Some of this may be due to drag, but no more than 2 or 3 meters.

QUESTION FROM FLOOR: How many satellites are there in the system?

DR. NEWTON: At present there are 3 satellites. Three satellites are all the Navy wants, and 3 satellites are all the Navy will get. If there is a demand for more satellites, that need will have to be made known. This is a political, not a technical matter.

(A discussion followed concerning the use of higher satellites so that the range might be increased. This portion of the taped recording was not clear enough to obtain an accurate transcription.)

DR. HEISKANEN: This discussion of satellite geodesy and physical geodesy further emphasizes the fact that the gravity anomalies are the most important part of the problem. From these gravity anomalies, we can compute the geoid and the details of the figure of the earth.

DR. NEWTON: Satellite and physical geodesy to complement each other.

QUESTION: How often are the ephemeris data corrected for the satellites?

DR. NEWTON: The ephemeris data are corrected on an average of every 12 hours. There is an injection station which passes under the satellite orbit about every 12 hours. It can run as much as 14 hours and, to give a safety factor, 16 hours of ephemeris data are injected.

QUESTION FROM FLOOR: You were going to explain the reason for the hole in the doughnut.

DR. NEWTON: Dr. Talwani and I both have evidence of a circular pattern of errors somewhat like a doughnut with a hole. I think it means that the dominant errors of the system, particularly those coming from an inadequate knowledge of the gravity field, plus the fact that the tracking data always come from exactly the same place, plus the fact that the navigator uses the satellite in a particular position, have a very high correlation. For a given direction and motion of the satellite , the errors always appear to be the same. In a series of measurements we find, in effect, that there are 4 average positions, one in each quadrant. The spacing or scattering of these points may be different in different parts of the earth, but at any one locality, the pattern is what I would expect to find. When you add to this, the other errors which are present, there is a scattering about the 4 points, with practically no scattering in the center. This accounts for the doughnut effect.

QUESTION FROM FLOOR: I would like to ask Mr. Jury what methods were used for determining the latitudes and longitudes of the points down range that he used for comparison with the positions he obtained from satellite geodesy.

MR. JURY: The positions on shore and down range are all on the North American 1927 Datum. The surveys down range had been made by Hiran for the basic control, with other electronic techniques being used for extensions from the basic control.

QUESTION FROM FLOOR: Isn't each camera referenced to the local gravity field and thus affected by the deflection of the vertical?

MR. JURY: The satellite is photographed against a stellar background simultaneously from 2 or more points. The deflection of the vertical is not involved. The gravity field might be involved indirectly in determining the height of the geoid under the ship. Actually, if the camera installation is on an isolated island, the results are obtained in X Y Z coordinates, from which a geoid height can be calculated.

DR. NETTLETON: How much do the changes in the ephemeris, which are injected into the satellite every 12 hours, amount to in position?

DR. NEWTON: Due to the fact that there is some delay between the time of tracking, the time of injecting, and time of using, the positions of the satellite in orbit may be degraded as much as 75 to 100 meters.

MR. DEAN: I want to expand a little on my paper given yesterday. The construction of the new Loran C station in Southern Indiana has been

started and it is expected to be finished by the end of the year. At that time, the accuracy contours which I showed in my last slide will be approximately correct. Also, the Coast Guard is moving the Master Station from Carolina Beach, North Carolina, to Wildwood, New Jersey, sometime later this year. This will cause another change in the coverage of the Loran C stations. If anyone is interested in using the network in the Gulf where better coverage will exist, the Oceanographic Office will be publishing tables for its use. There will be corrections for the overland path of the rays from the Indiana station. If anyone is interested in using the system and wants to get the best accuracy, I suggest they get in touch with me. I can give them what information I have, so that they can get the maximum precision out of the system.

(A discussion followed about the use of the Navy Satellite System to improve the isolated island datums. The recording was not clear enough to obtain a satisfactory verbatim transcription).

Activities and Developments in the U.S. Continental Shelf Regions—Motivations for Marine Geodesy

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INTRODUCTION AND BACKGROUND

The study of motivation is properly within the realm of psychology. Accordingly, during the preparation of this paper the psychologist in our Geophysics Group was consulted to obtain an accurate definition of the term motivation. She generously provided us with a definition which we are pleased to pass on to you: "Motivation is identified as one or a combination of three kinds of things: (1) an environmental determinant which precipitates the behavior in question, that is, the application of some irresistible force which of necessity leads to an action; (2) the internal urge, emotion, drive, instinct, demand, aspiration, desire, or interest which gives energy for the action; or (3) the incentive, goal, or object value which attracts or repels the organism."

Not being psychologists, we were not certain just what this meant. So we went to the dictionary where we found various synonyms: inducement, goad, incentive, impulse, spur, and spring, but no really good definition. Armed with this information, we went back to the psychologist for clarification. In deference to our ignorance, she reduced her definition to our level of understanding: "Motivation is why we do what we do!"

After listening to the previous speakers, the speakers in this session could claim that, instead of only one session on motivations for marine geodesy, there are really six sessions on the topic in this Symposium. In this session we will be hard pressed to match the testimonials for marine geodesy that have been heard over the past 2 1/2 days from members of the scientific, industrial, legal, space, and defense communities. So any assessment of motivations arising out of this meeting will need to consider carefully what has been presented before this paper.

An important, if not the first, step in the evolution of motivations is the identification of a problem, need, or desire. Ultimately, the evolutionary process reaches the stage where motivations can be stated as an objective. We would hazard a guess that the number of objectives represented in this auditorium is somewhere near the number in attendance. But we wonder if all objectives are not implicit in, or could not be derived from, an objective such as the one for a National Ocean Program as recommended by the Panel on Oceanography of the President's Science Advisory Committee in June 1966: ". . . effective use of the sea by man for all purposes considered for the terrestrial environment: commerce, industry, recreation, and settlement; as well as for knowledge and understanding."

Later on we will refer to land analogies for marine geodesy. You may want to think about a hypothetical symposium that could have taken place in 1866, a century ago. The theme of the hypothetical symposium was "Land Geodesy—Present and Future." The objective of a national land program had just been recommended—effective use of the land by man . . . . You may also want to think about land geodesy's contribution to the effective use of the land since our hypothetical symposium 100 years ago.

Returning to the present, we, as some of the previous speakers, shall be describing problems,

but problems in terms of needs stemming from the numerous interests, missions, and economic activities in the U.S. Continental-Shelf regions. We stress "U.S. Continental-Shelf regions" because estuaries, bays, shore areas, etc., are included in our discussions even though the term "shelf" is used for the sake of brevity. The approach differs from some treatments of this topic in that the needs will be described, first, within the 1964 gross economic environment of the U.S. shelf, and second, with regard to motivations for marine geodesy. So, in a sense, we are taking a first step toward a technical and economic prospectus to position marine geodesy within a universe of demands and desires arising from U.S. shelf activities.

Each of you undoubtedly has your opinion concerning motivations for marine geodesy, depending upon your own interests and activities. You may or may not concur with points made here, but if this paper does three things-call to your attention the gross economic setting associated with shelf problems, suggest that motivations for marine geodesy do exist, and finally, stimulate your thinking toward further delineration of marine geodesy's roles in effective use of the sea—then we believe it will have been a success.

Acknowledgement.—Some of the information which follows was obtained by the Battelle Memorial Institute during an investigation of the Nation's needs in Continental Shelf regions--conducted for, and under contract with, the Coast and Geodetic Survey over a 14-week period in the summer of 1965 and made available by the Environmental Science Services Administration through the U.S. Government Printing Office [*Development Potential of U.S. Continental Shelves,* U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, U.S. Government Printing Office, Washington, D.C., 20402, April 1966, price $1.25]. Those desiring additional information may want to refer to this report.

DISCUSSION

A breakdown of the over $21 billion in total economic activity in the U.S. Continental Shelf in 1964 by major groups is shown in table 1. These breakdowns, along with some examples of needs, will be discussed. A word of caution at this point: Do not compare or rank the dollar volumes between and among the various groups because methods of assessing dollar volumes are not constant across the ten groups.

Mining and Petroleum

Some difficulties were encountered in getting data for mining and petroleum activities in table 2 because estimates for 1964 operations and investments could be made for the petroleum industry but not for mining and mineral extraction industry. Because of this and for other reasons, the total shelf-related activity of $21.4 billion is probably a conservative estimate.

The needs of this group can be summarized as a requirement for systematic surveying, sampling, and mapping of the shelf. Obviously, response to this requirement can be only on the basis of priorities yet to be established. The ultimate need is for predictive capabilities based on reliable indicators or models of mineral deposits established through experience.

Table 1.—Economic Activity in U.S. Continental-Shelf Regions, Calendar Year 1964 or Fiscal Year 1965

(In millions of dollars)

Mining and petroleum	$1,704
Marine engineering	2,320
Recreation	3,855
Health and welfare	372
Transportation (1963 data)	11,280
Food and agriculture	345
Defense and space	1,319
Research and development	232
Other industry	10
State and local agencies	Included above.
Total	$21,437

Table 2.—Mining and Petroleum Economic Activity

(In millions of dollars)

Oil and gas:	
Production	$779
Exploration	51
Rig construction	45
Pipelines	50
Leases	306
Drilling operations	330
Minerals:	
Extracted from water	98
Dredged from floor bottom	30
Mined from subfloor	15
Total	$1,704

A very common need expressed within these industries is for improved methods of positioning. Positioning problems apparently have not been too demanding in the near-offshore regions, but the concern is that they, will become much more dif-

ficult to solve as shelf operations extend seaward and distances of offshore exploration become greater.

Similarly, at increased distances from shore, prediction of weather and wave conditions, currents, and bottom conditions for operations and construction will become of increasing interest.

Marine Engineering

In 1964, Marine Engineering activities totalled $2.3 billion in the U. S. continental shelf area (*see* table 3). Growing demands for data on processes occurring in shelf regions can be expected to arise not only from Marine Engineering activities, but also from associated needs in Recreation and Transportation. Additional attention will have to be given to the problems of winds and waves, tides and surges, inshore and estaurine dynamics, littoral transport of sediments, scour, sediment sources, etc., to reduce deficiencies in design criteria for maintenance, construction, and protection of beach and offshore facilities of many purposes and types.

Table 3.—Marine Engineering Economic Activity

(In millions of dollars)

Tsunami and hurricane protection construction	$18.7
Harbor, channel, and other construction and maintenance	106.0
Shipbuilding	2,189.0
Salvage value and service	6.7
Total	$2,320.4

Recreation

We will pass rapidly by Recreation calling your attention only to what is perhaps an unexpectedly large industry total of shelf-related economic activity—$3.8 billion (*see* table 4). Recreation in the shelf regions is a large industry, and one faced with the problem of expanding and competitive usage of a finite resource.

Table 4.—Recreation Economic Activity

(In millions of dollars)

Swimming	$1,495
Surfing	50
Skin diving	300
Pleasure boating	650
Sports fishing	760
National park activities	600
State and local park activities	ND
Private resorts	ND
Total	$3,855

Health and Welfare

The total of $372 million for Health and Welfare activities does not include the negative tsunami activity of $309 million estimated losses in 1964 (*see* table 5). Time permits only a brief remark on the needs in this group: They bring into sharp focus problems associated with the diverse and often conflicting uses of the shelf regions—that is, they highlight the dilemma between satisfying the market demands for recreation and fish foods in contrast to providing the areas needed for disposal of wastes.

Table 5.—Health and Welfare Economic Activity

(In millions of dollars)

Waste treatment and disposal	$200.0
Operations equipment investment	135.0
Pollution control	6.5
Desalination	30.0
Tsuanami losses	(309.0)
Total	$371.5

Transportation

The priority Transportation needs are not too pertinent to this Symposium, but a brief look at the type of activities involved in the $11.2 billion shelf-related estimate in table 6 is revealing.

Table 6.—Transportation Economic Activity

(In millions of dollars)

Freight revenues	$6,000
Passenger revenues	400
Port income	4,567
Roadway construction	100
Port investments	213
Property damage	(22)
Total	$11,280

Food and Agriculture

In arriving at the $345-million estimate given in table 7, some difficulties were encountered in identifying fish that came from shelf waters. The principal needs of the fishing industry (excluding legal matters) are three: (1) improved prediction of catch locations, (2) additional navigational aids, and (3) culture and protection of fish and shell-fish populations.

Table 7.—Food and Agriculture Economic Activity

(In millions of dollars)

Fishing (dockside value)	$326.0
Fishing equipment investment	15.0
Seaweed harvest	2.7
Seaweed equipment investment	1.5
Total	$345.2

Defense and Space

In the areas of Defense and Space, also, we were not bothered with truckloads of data for estimating economic activities (*see* table 8). Obviously, acquiring meaningful data in this broad area would be extremely difficult. Probably the estimate is conservative.

We have already heard about some requirements and views, mostly deep-ocean, perhaps, of Department of Defense and of National Aeronautic and Space Agency relative to marine geodesy. We have also heard about the concept of a marine geodetic range [see also Mourad and Frazier, 1965]. With respect to all of these, there are some problems in development and application of geodetic techniques.

Other needs, judging from the literature, cover the gamut of elements which make up the marine environment. These needs exist from the design and test stage to the operational phases of tactical sea-going activities. Scattering layers, bottom topography, velocity profiles, and other factors all have controlling influences on the eyes and ears of acoustic systems and, obviously, on marine geodesy.

Table 8.—Defense and Space Economic Activity

(In millions of dollars)

Navy:	
Ship movement	$630
ASW operations	200
Military construction	94
Other purchases	150
Other Department of Defense	ND
Aerospace	ND
Coast Guard	204
Coast Guard rescue	(2,100)
Total	$1,278

Research and Development

Some bookkeeping difficulties were encountered when deciding what dollars to assign to Research and Development. The total of $232 million (*see* table 9) could just as well have been $283 million if the $51 million for geophysical surveys by the oil and gas industry had been included under Research and Development instead of under the Mining and Petroleum. The shelf portion of the National Oceanographic Program surveys, totaling $12 million, was included as Research and Development. The total estimate of $40 million for shelf R&D within the National Oceanographic Program was derived from data provided by the Interagency Committee on Oceanography.

As for needs, Research and Development people seldom, if ever, have enough information. Composition and physical properties of sediments and cores is one of the more commonly expressed needs in terms of both numbers and descriptions of samples. Common to the work of many investigators are problems associated with the lack of physical and chemical data on waters and the need for more geophysical surveys and subsurface studies of the continental shelf and slope regions. The desire to better position the results of surveys for many purposes is also prevalent within this group. So, the Research and Development needs can be summarized as the desire for greater comprehensiveness, accuracy, and currency of time-dependent and thematic data.

Table 9.—Research and Development Economic Activity

(In millions of dollars)

National Oceanographic Program research and development	$28.0
Other Government research and development	19.3
National Oceanographic Program surveys	12.0
Navy research and development and test and evaluation	140.0
Oil and gas industry	26.5
Mining industry	2.0
Aerospace and defense industry	3.0
Other industry	1.0
Total	$231.8

TOTAL ECONOMIC ACTIVITY AND NEEDS IN U.S. SHELF REGIONS

To avoid the time gavel of the Session Chairman, the $21 billion economic environment as well as the spectrum of needs are treated in a succinct manner. Actually, a detailed description of the needs in each area would be quite repetitious. Another way of viewing this total is to consider that $1.2 billion in resources (oil, gas, fish, etc.) were taken from the U.S. shelf-regions in 1964; ship and cargo salvage value amounted to over $6 mil-

lion; and the remaining $20.2 billion consisted of income, investments, and expenditures associated with the services, missions, and activities of private and governmental pursuits.

Initially, there was some surprise that, within the scope of the study objectives, needs receiving the most emphasis during the survey were basically four:

(1) Maps of bottom topography.
(2) Information about mineral composition and properties of bottom materials—sediments and cores.
(3) Synoptic data from simultaneous measurements of currents in nearshore and the estuarine waters.
(4) Ability to determine and/or reoccupy more precisely the position of points on sea, in the sea, and on the sea bottom—or marine geodesy.

Not only is marine geodesy one of the indicated needs of those engaged in activities on the shelf, but also marine goedesy is inherent in two of the other needs: accuracte control for maps of bottom topography and distribution of bottom materials and other phenomena in the marine environment. The distribution of these four needs by groups is shown in table 10.

After thinking about the situation, our concern and surprise vanished. What had been revealed were four needs which have direct analogies and

Table 10.—Basic Information Needs

	Maps of bottom topography	Bottom materials, sediments, and cores	Synoptic data	Position-ing
Mining and petroleum	X	X	X	X
Marine engineering	X	X	X	..
Recreation	X	X	X	..
Health and welfare	X	..	X	..
Transportation	X	..	..	..
Food and agriculture	X	..	X	X
Defense and space	X	X	X	X
Research and development	X	X	X	X
Other industry	X	..	..	X

counterparts in systematic past, present, and anticipated developments on land.

Basic to everything is the need for better positioning and accurate control for mapping. This need has existed and continues to exist on land, and geodesists and others have established, and continue to establish and maintain, networks of horizontal and vertical control of various orders for many purposes. If we call these land networks products of land geodesy, we can now say we have the marine counterpart—marine geodesy products—in demand.

The counterpart of land topographic maps is, of course, maps of bottom topography. Once maps of the land surface have been prepared, all sorts of endeavors arise concerned with representing thematic data, properly positioned, on maps controlled by the geodetic land networks. The need for marine counterparts, in this case, is still at a very basic level—needed are descriptions, increased number of samples, and the indicated distribution of bottom materials and cores.

Weather and climatic data for the atmosphere have their marine counterparts in synoptic data needed for the liquid marine environment, particularly with regard to circulation patterns required for study and prediction of diffusion rates of pollutants.

The consensus is that there is a great demand for some very basic data and services with respect to the shelf. On land, satisfying these needs is now considered rather routine and is too often taken for granted. Marine geodesy has a fundamental role to play and appropriate techniques, procedures, systems, and uses can and are now beginning to be defined in response to this demand. Based on our studies, this response, to a large degree, does not require basic research. Rather, it is mostly a matter of adopting, applying and focusing the known state of the art in a well-planned manner.

MEASURING THE MOTIVATIONS FOR MARINE GEODESY

We have been talking today of a variety of needs associated with major groups interested in the Continental Shelf. Now that a beginning has been

made to view these needs in a marine-geodetic perspective, one might expect present technology and practices, as well as future developments, to become more oriented toward marine geodesy. Constraining this orientation will be needs carrying highest priority, a problem in itself and one which poses an additional problem of evaluating and measuring motivations.

Marine geodesy, as well as other sciences and technologies, is and will continue to be motivated through the confluence of two forces: first, professional interest in and/or possible solutions to specific scientific and engineering problems, and second, the practical need for solutions to these problems. Motivation then is a function of scientific and engineering capabilities and interests and of the needs of industry and government. All sorts of weighting factors are involved, but normally the practical and economic need factors carry the highest weight of them all. While there is usually professional motivation to pursue most technical subjects at any given time, such motivation takes on more impressive dimensions after some worthwhile user needs appear. Thus, the phase relation between the technical and need forces is obviously an important factor.

We have been studying marine geodesy within various approaches to evaluate and measure the motivations. Although we are not in a position to give quantitative results here, just on the basis of this Symposium alone the future for marine geodesy holds great promise. The logical conclusion seems to be that we should continue our efforts to define and pursue marine geodesy in a realistic manner as soon as possible, and certainly before any rush to the sea becomes binding.

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Bathymetric Maps for Continental Shelf Development

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The "Natural Resources of the Deep" are beginning to be explored with vigor, skill, and resolve. The technology of the deep ocean can and will be extended. Within the past several years a general national awareness has developed regarding the economic benefits to be derived from the exploitation of the resources of our Continental Shelf. This awareness was contributed to on June 10, 1964, by our becoming a signatory to the Convention on the Continental Shelf, at the United Nations Conference on the Law Of The Sea. At this time, the United States acquired about 850,000 square miles of additional territory. P.L. 89-454—The Marine Resources and Development Act of 1966; The Report of the President's Science Advisory Committee, and The President's remarks during the Commissioning ceremony for the USC&GS ship *Oceanographer* on July 13, 1966, all clearly show the importance of developing the Continental Shelf.

Mapping the Continental Shelf, in the broad sense, includes many different types of data presentations in order to catalog and conduct studies of temperature, gravity, magnetism, bottom and subbottom geology, and other elements associated with the sea. The understanding of this information requires a knowledge of the configuration of the ocean bottom for presentation on small- or large-scale bathymetric or underwater topographic maps. These detailed maps are required as a base for use in establishing an inventory of economic worth that must precede any comprehensive plans for exploitation and development for such industrial activities as fishing, mining, food, pollution control, and other activities associated with the prediction and modification of the ocean environment.

The bathymetric map maker is faced with the monumental task of evaluating and utilizing vast quantities of existing hydrographic data as well as collecting, processing, and utilizing new data to provide the required information to meet present and future needs. The inventory of existing data has been accumulated over the years in support of various activities associated with the sea. There is little that can be done to alter the quality of this information. We can, however, identify the quality and manipulate the data to a machine-processable form that is adaptable to computer and plotter technology for more efficient distribution and map production.

Many areas, where data are insufficient or inadequate, must be resurveyed before the mapmaker can proceed with his task. Marine geodesy must play an important role in the development of systems for determining precise position location. It also must provide accurate data relating to the size and shape of the earth for the construction of graphic projections. A major requirement is the establishment of coordinate points in the oceans, as well as on land, to provide the basic mapping control network. The Coast and Geodetic Survey has established about 500,000 permanent horizontal and vertical control points in the land areas of the United States. These stations represent our national geodetic control network. They are used to establish a grid that provides for the construction of accurate maps and charts. However, the establishment of similar permanent markers on and under the water has been difficult due to the lack of platforms and positioning systems for the precise measurements required.

Recent advancements in electronic surveying and the use of satellites for geodetic purposes now make it possible to accurately measure long distances in the ocean environment. Improved sonar techniques and underwater acoustic devices make possible the establishment of permanent marine bench marks. The establishment of an oceanic system of marked geodetic control points is now technically and economically feasible. Geodetic control in water areas, beyond the range of land-based positions, must be available before accurate

surveys and maps can be made. Users of this map information must have an adequate means of establishing and reoccupying positions in relation to the graphic data.

Requirements for map accuracies are determined by the needs of the ultimate users of the information portrayed. In determining the horizontal position accuracies for bathymetric maps, consideration must be given to military, scientific, and economic requirements. Map accuracies are determined for such diverse and interrelated activities as navigation, both surface and subsurface, military weapons systems, search and recovery, boundary delineation, equipment positioning and retrieval, and many other needs. There is a demonstrated need at the present time for horizontal position accuracies of ± 50 feet in the open sea from 300 to 1,000 miles from shore, and ± 100 feet in the deep ocean beyond this limit.

The Continental Shelf area of the United States and its territories is one-fourth that of the total U.S. land surface, or about 850,000 square statute miles. The Continental Shelf as defined by international law states that the seabed off our coasts is essentially ours as far out as we can exploit the resources, but also exposes the seabed outside the 200 meter depth to exploitation and claim by other nations (fig. 1).

Figure 2 is an example of a bathymetric map representing a section of the Atlantic Coast. The shape of the bottom is shown by closely spaced contours that are accentuated by tints and colors for easier interpretation of the various features.

The compilation of submarine topography is much more difficult than land topography because the features to be mapped are largely concealed from view. Extensive plains of sediment, undersea mountain ranges, isolated submerged mountain peaks rising thousands of feet above the sea bottom, and underwater escarpments a mile or more in height are all present on the sea floor. The correct interpretation of depth soundings, subbottom profiles, and other data for bathymetric mapping depends upon the cartographers oceanographic experience and his knowledge of geology and submarine topography. The accuracy of a bathymetric map depends upon the basic survey coverage of the area, the density and accuracy of control, and the correct interpretation and application of available data.

Priority areas for bathymetric mapping are established to implement the National goals for oceanography where "comprehension" of the ocean

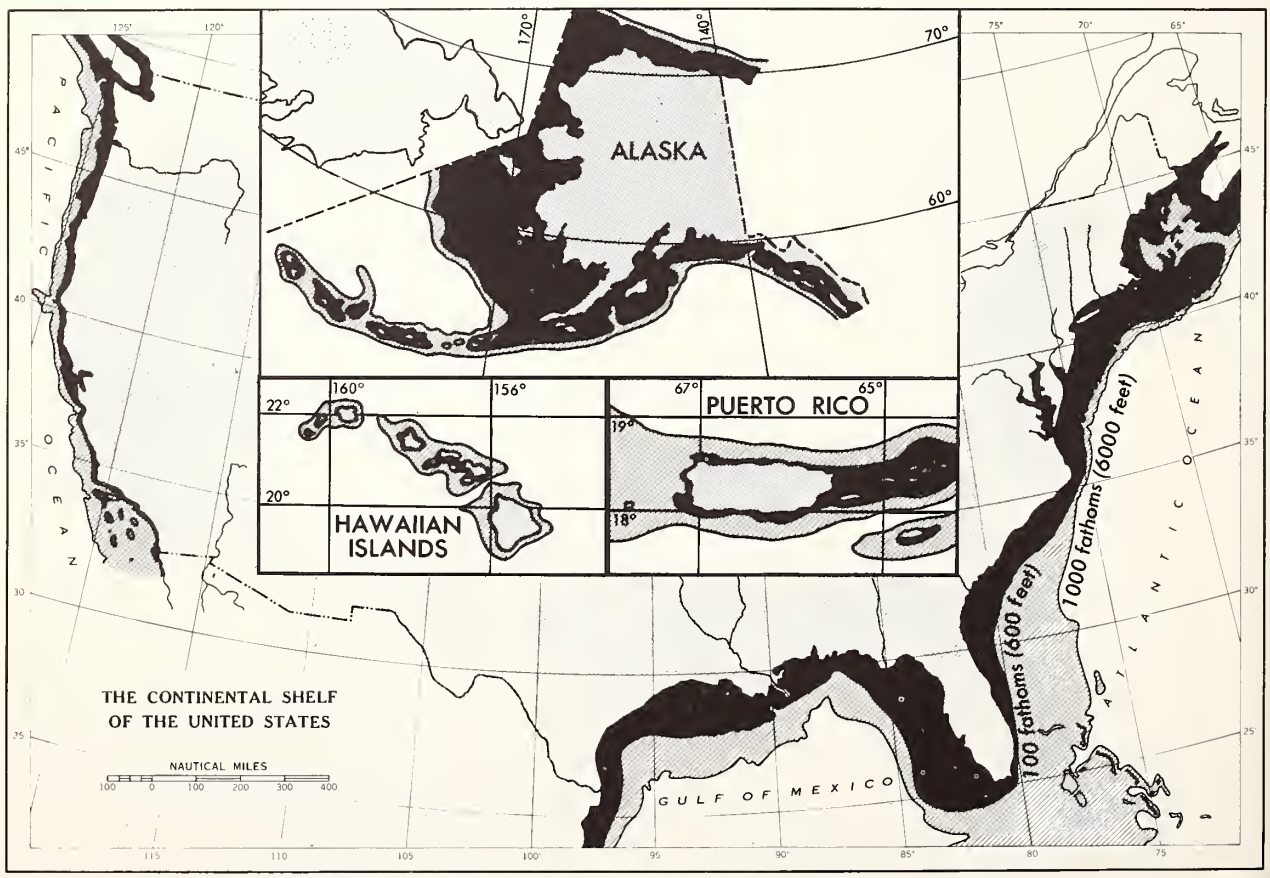

FIGURE 1.—Continental Shelf area of the United States.

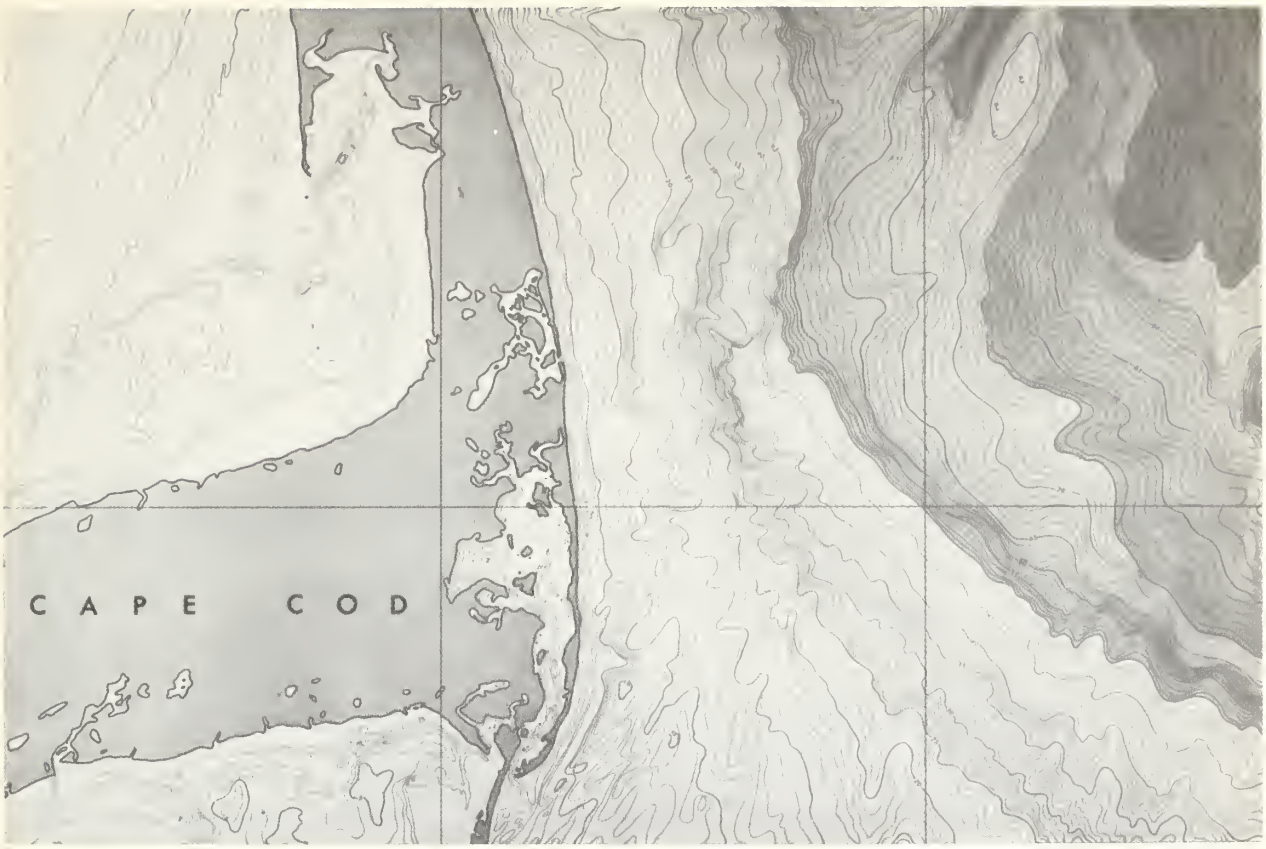

FIGURE 2.—Example of bathymetric map showing features accentuated by tints and colors—Coast and Geodetic Survey 1:125,000 scale series.

environment may be expected to provide the greatest benefits in the public interest, and to be of maximum value to various user groups. Mapping projects now underway in the Coast and Geodetic Survey consist of a basic 1:250,000 scale series for the Continental Shelf, supplemented by a 1:125,000 scale series of the Mid-Atlantic Shelf area (published in cooperation with the U.S. Bureau of Commercial Fisheries) and a 1:400,000 scale series of the Aleutian Arc (figs. 3 and 4). The basic mapping plan provides for publishing these maps during the next 5-year period for selected priority areas.

To accomplish the National goal and implement the objectives set forth by the President's Science Advisory Committee in the report *Effective Use of the Sea* will require the vigorous participation of marine geodesy to provide for precise geodetic control in the marine environment. Exploitation and development of the vast natural resources off our coasts to meet the needs of government and industry can only be met by continued development of existing geodetic control systems for more accurate map and chart production to help man find new and better ways to determine his position on earth.

Up to the present time industrial investment in Continental Shelf activity has been primarily devoted to profitable offshore oil production. Now "the hunters" are expanding their efforts and much of their success depends on the availability of adequate bathymetric maps.

FIGURE 3.—Coast and Geodetic Survey bathymetric map index for 1:250,000 scale series for Continental Shelf and 1:125,000 scale series for Mid-Atlantic Shelf area.

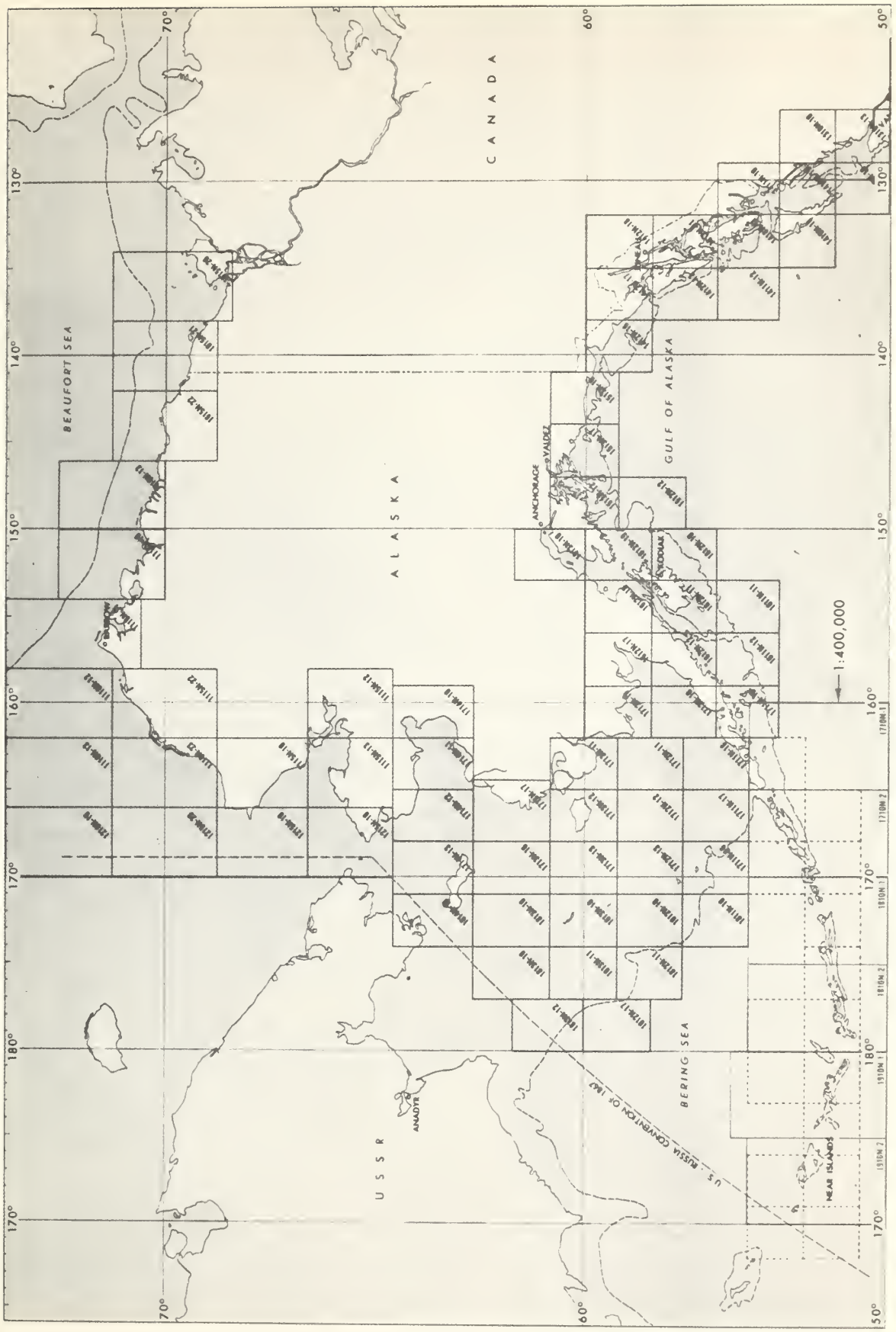

FIGURE 4.—Coast and Geodetic Survey bathymetric map index for 1:250,000 scale series for Continental Shelf and 1:400,000 scale series for Aleutian Arc.

The Economic Motivation—Geology and Geophysics for Oil and Mineral Exploration

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INTRODUCTION

Marine geology, as applied in oil exploration, is based almost entirely on geophysics. The applications of the same fundamental principles of seismic, gravity, and magnetic methods as developed over some 40 years, have been adapted for use at sea. The field of application is primarily on the continental shelves defined as areas of water depths of 600 feet or less. Geophysics on the shelves, most notably in offshore Louisiana, has led to important oil production and establishment of large reserves.

This paper outlines the methods used, the geodetic requirements, particularly in navigation, the exploration costs, and the importance of marine geodesy in these costs. Finally, estimates are made of the total costs of petroleum exploration in offshore Louisiana and of the production and reserves established. These figures show that much more has been expended than has yet been returned from these operations. The motivation for continued offshore exploration is the substantial reserves established in the Texas-Louisiana offshore and other areas and the belief that tremendous reserves remain to be found in the great volume of sediments on the continental shelves.

Geophysical exploration, as an aid to surface and subsurface geology, started in the Gulf Coast in the early 1920s with the application of the three physical principles which are the foundations of the magnetic, gravitational, and seismic methods. Other methods have had their hopeful beginnings, but, after over 40 years of application, geophysical work for petroleum exploration is still based on the measurement of magnetic and gravitational fields and on the propagation of elastic waves. There can be no surface geology in water-covered areas (except for a very limited amount done by skin divers). Therefore, offshore geology starts with geophysics and is followed by drilling.

Offshore geophysical work began in a very small way in the Gulf of Mexico before World War II but its real application began in 1946 after the war. Gravity and seismic exploration developed fairly rapidly, followed by the first offshore drilling which was done from fixed platforms on piling. The offshore geology for oil exploration is very similar, in the application of geophysical techniques and of subsurface geology from the subsequent drilling, to the procedures which had been used extensively in the adjacent Gulf Coast where comparatively little effective exploration can be based on surface geology. In its application to marine geophysics, there has been very extensive development of instrumentation, particularly in the seismic and gravity methods but no change in the physical and geological fundamentals.

MARINE SEISMIC OPERATIONS

The seismic offshore reflection method has now become quite complex. The detectors are in long cables, up to one and a half miles long, with each cable commonly carrying twenty-four channels, with each channel receiving energy from as many as twenty equally spaced detectors so that a cable may contain some hundreds of individual seismometers. For many years the only energy source was dynamite or other explosives. With a wide open ocean to work in, the operations are free of fences, topography, etc., and are limited only by the techniques employed and the weather and water conditions. Systems were soon developed for almost continuous operation with dynamite explosions being set off at intervals of only a very few minutes. In recent years, other energy sources have come into somewhat limited use. Spark discharges are used with up to 100 kilojoules (equivalent to approximately 75 thousand foot pounds) for each discharge. Gas explosions in a "gun" or tube in the water and gas

discharges in a flexible rubber tube are being used to some extent.

Most of the seismic data are now recorded on magnetic tape. Individual records are mixed or stacked in various ways with the aim of improving the signal to noise ratio so that reflections can be recognized among other disturbances. With digital recording, signals can be processed in an electronic computer operation to improve the signal to noise ratio, particularly the "ringing" or repetition of the signal due to reflection between the surface and bottom of the water. All these operations have greatly increased the cost of the seismic operation itself, but there has been compensation in that the speed has been greatly increased over that attained on land. Even with a cost for a seismic crew of the order of $125,000 per month, the cost per line mile can be kept to the order of $300 to $500 including close shooting and very extensive data processing.

MARINE GRAVITY

The first extensive marine gravity operations were made in a diving bell containing a gravity meter and a very cramped operator who read the meter as on land. This type measurement was soon replaced by the use of a land gravity meter enclosed in a suitable shell with electronic devices which permit the operation of the meter in much the same way as if done by hand. It was found in the earliest use of meters on the relatively soft and shallow bottom off the Texas and Louisiana coast, that there was always some motion of the bottom. This motional difficulty was overcome by use of an "elevator" which counters the vertical motion of the case by an opposite vertical motion of the meter itself relative to the case with the meter beam acting as a seismograph to control that motion. In another development, the motional disturbance is removed by using a highly damped moving system and measuring changes in the rate of deflection of the meter moving system rather than the deflection itself to measure changes in gravity.

The final development is that of an instrument which can be mounted in a ship and can make continuous gravity measurements while the ship is under way. This means, of course, that gravity must be measured in the disturbing environment of the accelerations due to the motions of the ship. This corresponds to measuring a very small quantity, i.e., the true value of gravity, in a field of very strong but relatively short period disturbances. The vertical component of these disturbances can be averaged in time, as their mean value is zero. The horizontal disturbances are a more difficult problem. In one system the gravity meter swings freely on gimbals, and its angle from the vertical is measured by reference to a long period level. This measurement provides a correction which modifies the beam position so that the effect of horizontal acceleration is eliminated in the meter output. In another system the meter is maintained level on a gyroscopically stabilized platform. There remain disturbing secondary effects such as cross coupling between horizontal and vertical accelerations and possible distortion of the moving system of the meter itself because of the forces due to the horizontal accelerations. Recent experience with a meter on a stabilized platform has shown considerable improvement over the earlier form with the gimbal suspension. From an operation currently under way in the Gulf of Mexico with a regular grid of lines, it is possible to determine the precision of the gravity measurement from the differences in gravity values at the line intersections. The median unadjusted difference at intersections is about 1.7 mg, and the random error, after adjustment for systematic line-by-line differences, is about 0.6 mg. With this precision and with a three to five mile grid of lines, the resulting gravity maps give sufficient detail to be very useful for petroleum exploration.

MARINE MAGNETICS

Magnetic observations over water-covered areas are being made routinely by airborne magnetometers and the operation is substantially the same as over land except for positioning are not applicable, and the marine surveys are usually made with some form of electronic positioning. In some cases, where lines are run out from shore control, Doppler navigation is used. Magnetic observations also are made with the instrument towed behind the ship. Until recently airborne and shipborn magnetic observations were made with fluxgate type magnetometers. Recently, nuclear precession and optically pumped instruments of very high sensitivity have come into use.

COMBINED GEOPHYSICAL OPERATIONS

The ultimate in marine geophysical operations is a combination in which all three methods—seismic, gravity, and magnetic—are carried out simultaneously. This uses a continuous seismic system of the sparker or gas-gun type, a shipborne gravity meter, preferably with a stabilized platform, and a towed magnetometer which can be of any of the types used for airborne magnetics. There is a very substantial economy in the combined operation since the relatively large ship and location costs are common to all three methods. The advantages of having the several types of geophysical data all on the same line and at the same time are obvious. The several types

of information complement one another to aid in the geological interpretation. The handling of the very large volume of data rapidly accumulated is greatly facilitated by recording on magnetic tape in a form suitable for processing on electronic computers.

MARINE GEODESY APPLIED TO OFFSHORE GEOPHYSICS

All of the operations discussed above require positioning of some kind. There is not much use in making a marine geophysical survey with the hope of using it to control other operations unless it is possible to map the results and return to a given spot when further exploration or drilling is decided upon. The entire development of location systems for offshore petroleum exploration is an application of "marine geodesy" although, generally, it is not considered in those terms. The development of positioning methods reviewed here is primarily with respect to their history in the Gulf of Mexico, but the same systems are now in use in many parts of the world.

The earliest offshore surveys were made by visual control. For inland waters or near offshore operations, locations were determined by sextant observations on fixed points on land or by transits from surveyed positions along the shore. This was possible where the shore line is accessible, as it is along the Texas beaches but along only a small portion of the Louisiana coast. In good weather such observations could be made to perhaps ten miles offshore. Observations were extended to about twenty-five miles offshore by working at night and observing a light on a balloon several hundred feet above the boat. For some early seismic operations, wire line measuring systems were used but were quite slow and cumbersome. A sonar system was used in early seismic work but had serious difficulties because the sonar buoys were picked up by fishermen who resented the intrusion of the geophysical crews. Some use was made of radar for positioning by using corner reflectors, but the useful range was quite limited.

The first electronic positioning used Shoran with surplus military equipment. This system uses ultra-high frequencies and is limited to line of sight distances. Along the Gulf Coast satisfactory Shoran signals, from towers up to 100 feet high, could be received up to about thirty to forty miles offshore. The phase comparison systems, using frequencies of around 2000 kcs and not limited by line of sight ranges, have now replaced the other systems along the Gulf Coast. The Raydist and Lorac systems were both put into operation there during 1951. Both systems have maintained survey nets along the entire coast of the Gulf of Mexico from Florida to South Texas more or less continuously for some fifteen years.

In the early days of exploration in the Gulf of Mexico grids of "land lines" were set up and now have been extended to approximately the 600-foot water-depth contour (fig. 1). These are a system of blocks, usually about three miles square, with boundaries defined in terms of offshore extensions of the state rectangular coordinate systems. Detail within one such system is shown by figure 2.

All of the geophysical work and subsequent leasing and drilling is defined in terms of these blocks. While, of course, nothing is visible, these "fence lines" are as real legally and economically as those which one would see in flying over farm land in a regularly sectionized area. There are no corner stakes, but a geophysical (or fishing) boat can come to a producing platform and find a sign naming the well and its location just as if it were on land. The reality of this whole "marine geodesy" system is entirely dependent on the radio location systems which are used to carry out all operations and locations in the area.

ECONOMIC FACTORS

Offshore petroleum exploration in the Gulf of Mexico and particularly off the Louisiana coast is the most highly developed anywhere in the world. It should be useful therefore to review the economic factors here as a measure of possible developments of the Continental Shelf areas with petroleum possibilities in other parts of the world.

The Louisiana offshore (fig. 1) is simply an extension into water-covered areas of the same geological conditions which have made the very prolific oil production of the salt dome belt of South Louisiana. Since about 1946, according to F. M. Ritchie [1966], Senior Vice President of Louisiana Land and Exploration Company, within the Louisiana offshore area, there has been paid out almost 1.3 billion dollars in lease bonuses, some 7,200 wells have been drilled, 182 oil and gas fields have been found. Offshore production was about 200 million barrels in 1965 and cumulative production to the end of 1965 about eleven hundred million barrels of which about 58 percent is in waters less than 40 feet deep, 37 percent in 40 to 100 feet and 4 percent over 100 feet. Proven reserves are estimated at 3.6 billion barrels and unproven reserves at 9 billion barrels.

These figures are very impressive but it must be kept in mind that this is one of the most favorable offshore provinces anywhere in the world, in that, as mentioned above, it is a natural extension of an already proven prolific area. Finding and developing this production has been very expensive partly because it was a pioneering operation.

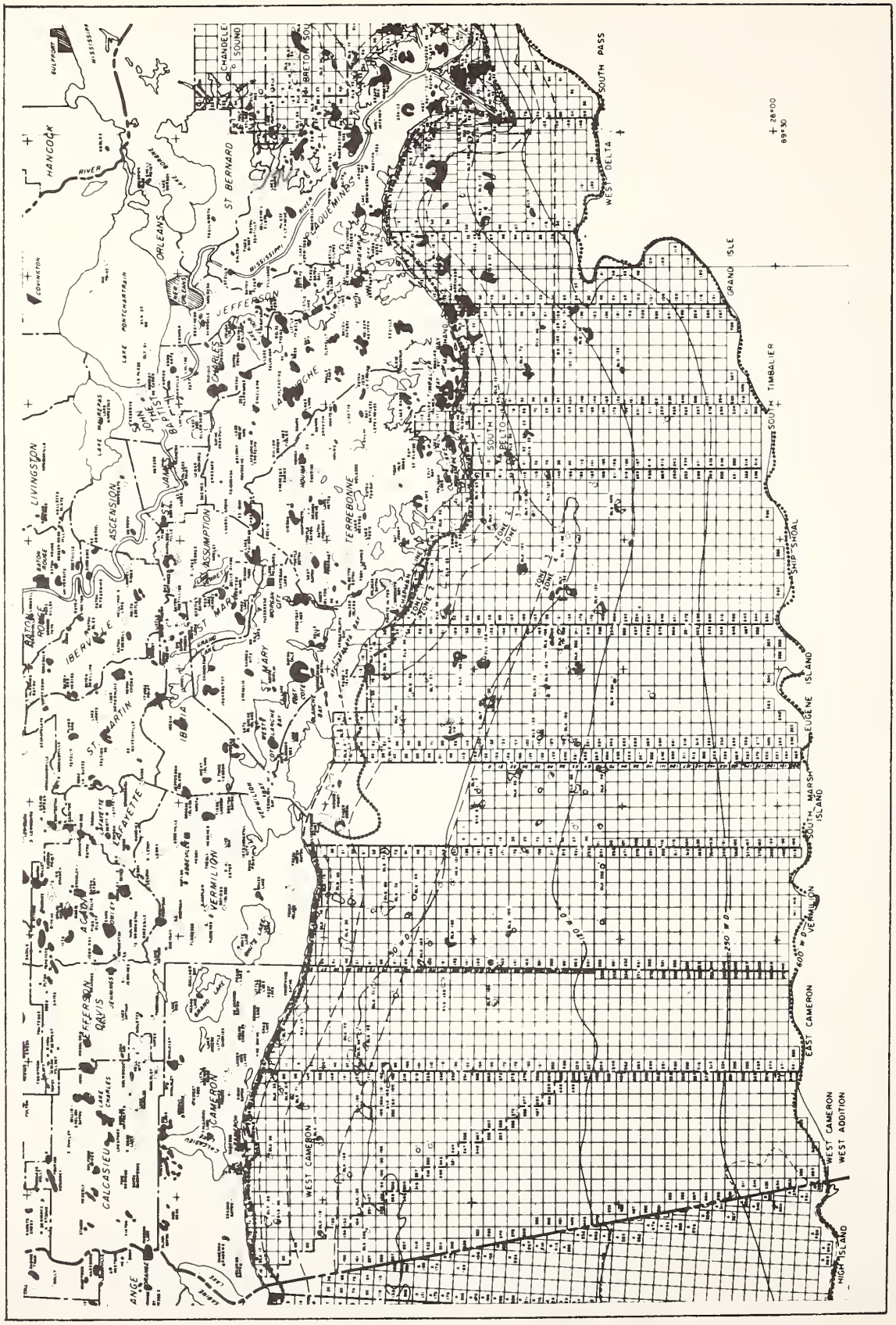

FIGURE 1.—Oil and Gas Fields and Offshore Location Nets, Louisiana Gulf Coast. (Courtesy Sidney Schafer and Associates)

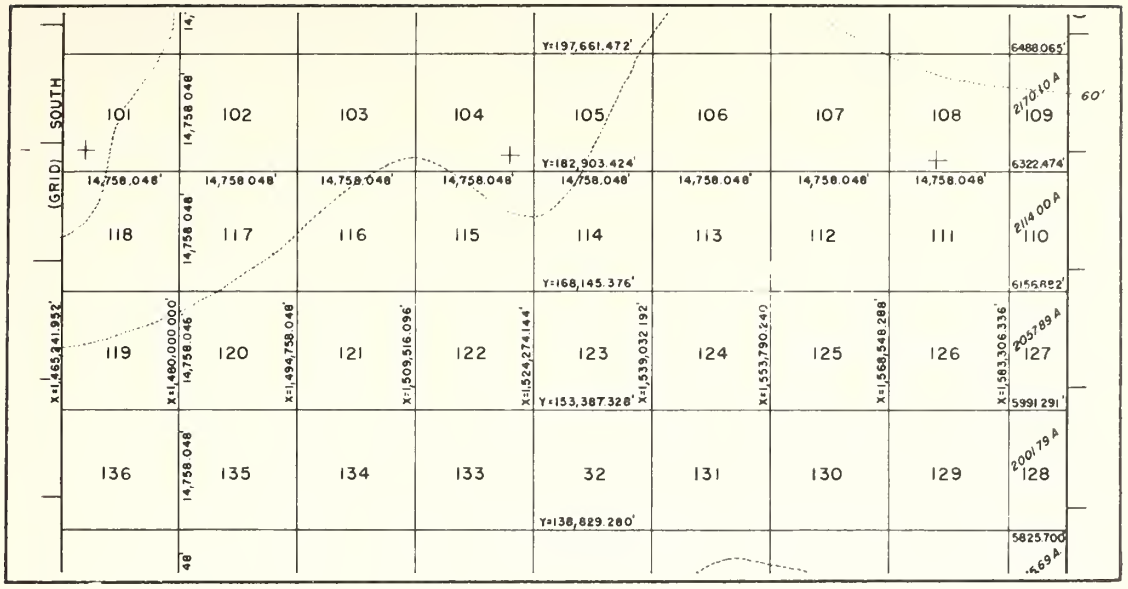

FIGURE 2.—Detail of portion of Outer Continental Shelf Leasing Map, U.S. Department of Interior, Bureau of Land Management.

It is estimated that to the end of 1965 the total lease bonus, geophysical, and drilling costs have been about 5.3 billion dollars. The approximate net value of the production to date is of the order of 3.5 billion dollars including 1/6 royalty which does not help pay for the costs. There is still a substantial deficit which the area must pay back to the petroleum industry in some indefinite time in the future after the "receipts" curve crosses that of expenditures.

The place of marine geodesy in all of these operations and the current petroleum exploration on continental shelves over the world is of fundamental importance as regards the scientific, technical, and administrative aspects which all depend on locations. Also, the maintenance and use of the radio location systems for petroleum exploration involves very substantial amounts of money. It is estimated that, at the present time, there are nearly 100 radio location nets operating over the Continental Shelf areas of various parts of the world. The annual expenditure for these positioning services is of the order of 12 to 15 million dollars. It is further estimated that the total expenditures since 1946 for location or "marine geodesy" services to the petroleum industry have been between 75 and 100 million dollars.

OTHER AREAS OF OFFSHORE EXPLORATION

The foregoing discussion has been confined largely to the Gulf Coast and particularly to the Louisiana offshore as an example of the contribution of marine geodesy to offshore petroleum geology and exploration. There are continental shelves in many other parts of the world where similar application of marine geodesy may be expected.

Shelves of widely varying width are present around the edges of most of the continental areas. Rather arbitrarily the Continental Shelf is commonly defined as the belt from shore to a depth of 100 fathoms or 600 feet. This turns out to be a fairly natural boundary because, in many parts of the world, the break between the relatively flat Continental Shelf, and the more steeply dipping Continental Slope begins at a depth of about 100 fathoms, and therefore this is a quite broadly applicable definition of the actual physiographic boundary.

Lewis Weeks [1965], formerly Chief Geologist of the Standard Oil Company of New Jersey, has made a careful estimate of the areas and petroleum potential of the continental shelves of the world. His review is summarized in the accompanying table (fig. 4) which shows that there are nearly 2 million square miles of offshore hunting grounds with good to fair petroleum prospects and some 4 million square miles more that are possibly worth some attention.

Weeks further estimates that the possible ultimate reserves of the "good" or Class A offshore areas are some 160 billion barrels and of the "fair" or Class B areas are some 500 billion barrels. Realization of anything approaching these huge figures would be very far into the future. *This possibility of very large petroleum reserves in the Continental Shelf sedimentary basins is the primary economic motivation for*

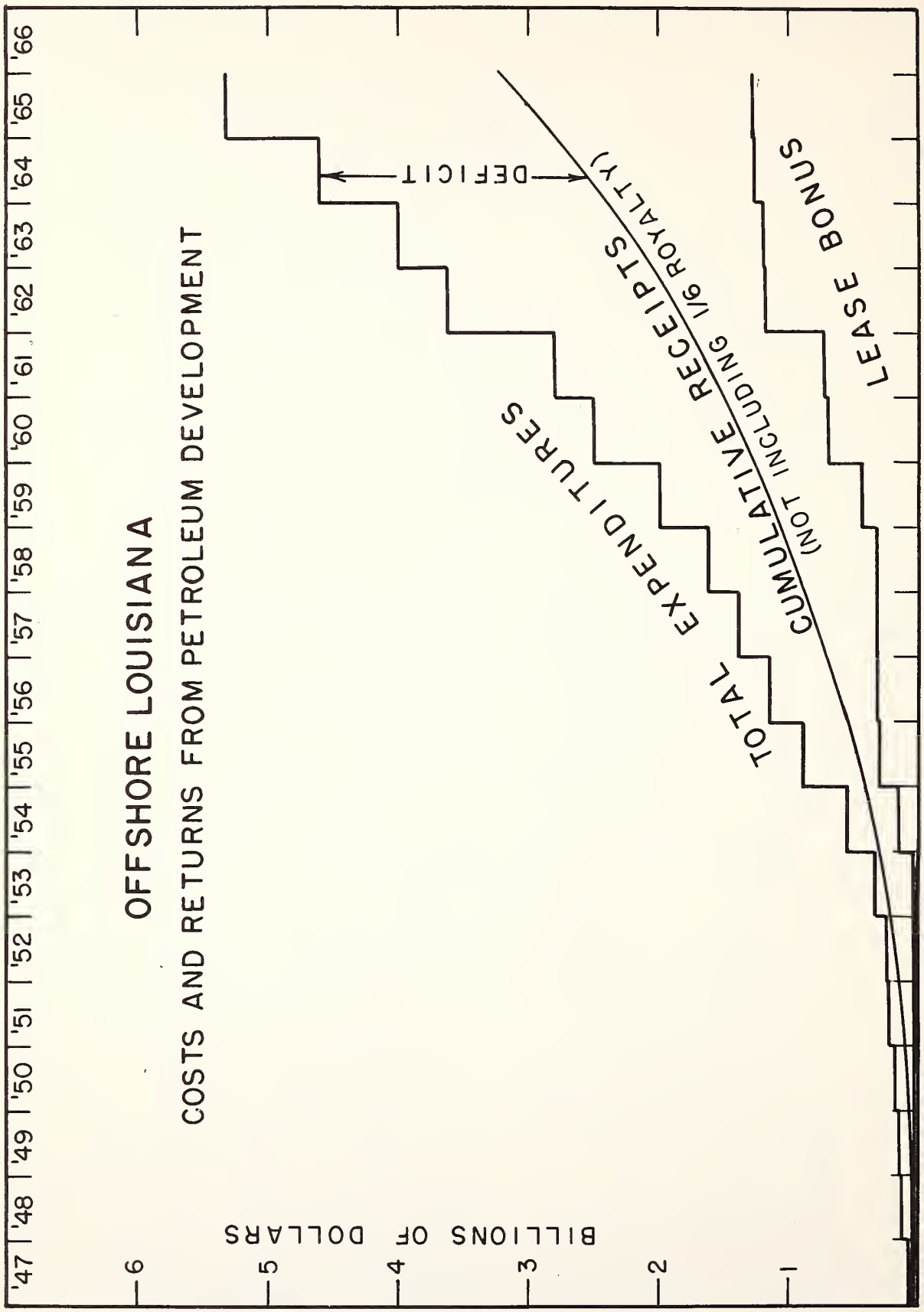

FIGURE 3.—Costs and Returns from Offshore Petroleum Development, Offshore Louisiana.

WORLD CONTINENTAL SHELF SEDIMENTARY BASIN AREAS
(THOUSANDS OF SQUARE MILES)

PROSPECTS →	GOOD	FAIR	POOR
NORTH AMERICA	40	315	875
SOUTH AMERICA	20	150	425
EUROPE	5	90	255
AFRICA	8	82	245
MIDDLE EAST, ASIA	40	65	67
FAR EAST, ASIA	5	110	285
EAST INDIES, PHILIPPINES	35	305	600
AUSTRALIA, NEW ZEALAND		130	405
ANTARCTICA		25	125
IRON CURTAIN COUNTRIES	35	385	1,043
	188	1,657	4,325

After L. G. Weeks, Bulletin AAPG, October 1965

FIGURE 4.—World Continental Shelf Sedimentary Basin Areas. (From L. G. Weeks)

the current interest and very large expenditures in offshore exploration. This is in spite of the fact that the Louisiana offshore, which quite possibly has better potential than most other shelf areas of the world, is still far behind in paying back to the oil industry the costs of geophysics and drilling and the accompanying marine geodesy.

In spite of the superficially rather unfavorable economic prospects indicated by this review and by the lack of payout to date in a very favorable area, the interest in marine exploration for petroleum is increasing rapidly. Much of this interest clearly must be ascribed to the existence of very large volumes of unexplored marine sediments which are attractive in comparison with any remaining, relatively unexplored areas on land.

At the present time very active geophysical and drilling operations are going on around the world. Currently active shelf areas include the California Coast, Cook Inlet in Alaska, the North Sea, particularly off the east coast of England, the Persian Gulf, the Red Sea, and Adriatic, the East Indies, the southeast coast of Australia, the West Coast of Africa, and some other areas. At the present time the greatest volume of offshore production is from the Persian Gulf. All these operations and the exploration preceding them are dependent on marine geodesy and in total, as mentioned above, this adds up to a very substantial activity. Nearly 100 operating nets providing radio location services, including Shoran, Raydist, Lorac, Decca, Toran are in service literally around the world. Each net provides location for from one to many exploration or drilling operations within it.

FUTURE GEODETIC REQUIREMENTS

Let us now consider the possibilities and limitations of the various marine geodesy systems as applied to petroleum exploration. For relatively nearshore locations (to approximately 100 miles offshore) and for daytime operation, the present medium frequency radio location systems are quite adequate for most geophysical operations. These systems usually are not applicable on a 24-hour basis because of the interference by "sky waves" near the sunrise and sunset hours which often prevent keeping a "lane count" through those periods. There has been some development of "lane identification" systems but, so far, these have not been very satisfactory and have not been put into general practice. For shelf areas adjacent to high topography, the range of Shoran can be extended by mounting the fixed transmitters at high elevations, and there are no sky waves to interrupt the signals. For example, off the California coast, Shoran positioning is used up to 170 miles offshore.

For some operations, far from shore, of which shipborne gravity is a particularly good example, it would be highly desirable to have a reasonably precise continuous positioning system. There is some hope that these requirements may be met

by a satellite navigation system but, at present, the complexities are considerable for routine application, fixes are available only periodically, and the attainable precision may not be adequate for close survey networks such as are now being used.

From the very recent developments reported at this meeting, it appears that the satellite navigation system may be reaching a degree of precision which would be very helpful if not entirely adequate for Continental Shelf exploration. Continuous worldwide positions are possible from the very low frequency (VLF) and Omega systems, based on stabilized transmitters using frequencies of 10 to 13 kc at widely spaced communication or special radio location stations. In areas where available, the Loran navigation system may be used, again for relatively widely spaced survey nets. None of these, however, are adequate for the relatively high precision needed for a close net of geophysical observations and for definition "land lines" for Continental Shelf exploration. Therefore, it seems that in the immediate future at least, offshore petroleum exploration will depend very largely on the presently available radio location systems, in spite of the limited range of the ultra-high frequency Shoran type and the difficulties of "sky wave" interference and lack of a reliable "lane count" for the intermediate frequency systems.

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Deep Submergence: Its Technical and Geodetic Implications

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Future generations may refer to the latter half of this century as the oceanic renaissance because of, rather than despite, the spectacular budgets and achievements in other fields such as outer space, atomic energy, communications, and data processing. This forecast is based on a careful assessment of the economic potential of the ocean and the many recent scientific and technical achievements that could provide, if properly organized and used, the capability to explore the global sea without imposing inordinate additional demands on our intellectual and material resources.

There are many diverse interests in deep submergence for comparable diverse reasons: the petroleum industry for economic reasons; the scientific community for pure oceanic knowledge; the U.S. Navy for strategic and tactical implications, to name a few. These efforts are necessarily highly specialized. In some areas one could almost consider them somewhat myopic and insular because of the circumscribed objectives, narrow personal interests, short-range vision, restricted goals, and limited budgets. These factors all contribute barriers, and consequently much valuable information remains insularly undiffused.

Potentially we have at our disposal today many new and powerful tools and techniques developed for other technologies that can be applied to deep submergence. In addition, from an increasing storehouse of practical experience in deep submergence, new tools and techniques as well as adaptive ones are evolving. This paper will examine several areas of deep submergence and by examples from actual experience highlight the present state-of-the-art, placing emphasis on geodetic implications. It will also stress how selected oceanic techniques might be interwoven with experience and methodology developed in other areas to provide a pattern of tested procedures and verified data from which solutions to many problems could be derived.

DEEP SUBMERGENCE EXPERIENCE

U.S. Navy Deep Submergence Systems Project (DSSP)

The tragic loss of the *Thresher* in 1963 triggered a most comprehensive study of the Navy's role in Deep Submergence. At the request of President Kennedy, and under direction of the Oceanographer of the Navy, the Deep Submergence Systems Review Group (DSSRG) was formed to assess the then existing state of the art and determine the Navy's short-range goals.

Four basic tasks were defined to be pursued over a basic 5-year period:

(1) Submarine Escape and Rescue
(2) Large-Object Salvage at Continental Shelf Depths
(3) Deep-Ocean Recovery
(4) Man-In-The-Sea Program

Presently these tasks are well underway, the originally planned research tools being supplemented by the inclusion of a small intermediate-depth nuclear-powered submersible, the NR-1.

There are a number of important requirements common to all of the tasks of DSSP as well as most other undersea work such as:

- Navigation systems—surface, subsurface, and bottom,

- Search and identification systems,
- Life-support systems,
- Underwater tools, including remote-control devices,
- Underwater workboats,
- Underwater power sources, and
- Environment-prediction systems.

Most of the problems discussed herein fall into the above categories. Considerable basic and applied research will be necessary on oceanic processes and properties before optimum solutions are available. In addition, there will be no substitute for experience gained probing the ocean's depth when feats are attempted which were virtually impossible a few short years ago.

A term coming into common usage to describe this practical application of the above towards desired ends is "Ocean Engineering." As we plan work through the air-sea interface, either from the surface or from within dry submersibles, or within the sea environment with free divers, we find that Ocean Engineering has two aspects. One is taking the results of basic and applied research and developing the tools, vehicles, and methodology necessary for successful pursuance of our goals; the other is taking these tools, vehicles, and methodology and accomplishing the desired tasks with them.

This latter facet of Ocean Engineering is as old as Noah and is commonly called "Seamanship." Those of you who have had to depend on gaining oceanic knowledge from surface vehicles know what we mean, watching as you have the ship's boatswains, riggers, and winch operators practice their art under arduous conditions to retrieve your data-collection devices. Those of us fortunate enough to observe the operation of dry submersibles and the work of deep free saturated divers appreciate the art of seamanship to a far greater degree.

I suspect the engineering by our astronauts in deep space could analogously be called "spacemanship." Analogy-seekers can have a field day with deep submergence and aerospace. The important point is that sophistication and automation in devices, tools, and methodology cannot remove the practical aspect, this "art of working and navigating a vessel," to use Webster's definition of seamanship.

This point was visibly rammed home to many experienced seamen last April 7 off Palomares, Spain. There the ultimate in weaponry our military technology could provide was recovered from a depth of 2,900 feet in an unprecedented feat of Ocean Engineering. However, the hoist which was used was made of mundane combinations of lines, blocks, and capstans, virtually unchanged since the days of the Phoenicians.

Search and Recovery Off Palmares, Spain

The greatest single effort yet mounted to deep submergence ends was the aforementioned operation (Aircraft Salvage Operations Mediterranean) officially known as AIRCRAFT SALVOPS MED. Here virtually all the pertinent knowledge and applicable material resources this nation could muster were assembled for the incredible task of searching for, locating, and recovering a nuclear weapon dropped as the result of a mid-air collision over the southeastern coast of Spain.

The U.S. Navy had the responsibility, when it became evident that the weapon had probably fallen into the sea, to locate and recover it. Upon specific request by the Air Force, the Navy mounted a gigantic effort. When the area of interest was evaluated and determined to extend from the shoreline to depths in excess of 4,000 feet, covering 100 square miles, a wide range of devices, vehicles, and systems were assembled.

Search Navigation. The geodetic implications of any underwater search operation are paramount. The correlation of geographic surface and bottom positions is a necessity to record and project search effort. The theory of a statistical search is is simple enough to allow search effectiveness probability to be calculated as a function of search effort. What is difficult is the quantifying of the uncertainties of the search effort.

Experience gained from the *Thresher* search operations during the summers of 1963 and 1964 was invaluable in determining immediate needs. Accurate surface navigation was mandatory and initially extremely poor. The only chart available of the area was a medium-scale chart originally compiled, in October 1935, from old Spanish charts. This was grossly inaccurate. Oceanographic Detachment Two aboard the USNS *Dutton* made some revisions, but plotting errors were still of the order of ± 300 yards. The installation of an electronic high-accuracy navigation system gave a satisfactory surface navigational accuracy of ± 12 feet.

Bottom navigation was another matter. When navigational uncertainties approach the search width, the search becomes random. The combined accuracy of all available systems was far from the accuracy required to allow anything but a random search. In addition, the electronic search systems could not adequately classify contacts. Whenever an electronic (sonar) contact was made, its position was plotted and later revisited for positive identification. The correlation between the contact identified (when it was relocated at all) and the original sonar contact was extremely poor.

There were errors in bathymetric measurements compounding the problems in bottom navi-

gation in the many areas of precipitous terrain. It is said that the topography of a coastal sea bottom is reflected in the topography of the shore. This was certainly true off Palomares. The rugged coastal mountain range could have been the mirror image of the ocean bottom.

Vehicles and Devices. A great number of devices and vehicles were employed off Spain. It became obvious that each had certain limitations and advantages which had to be considered for optimum employment. Some equipment was not used at all after initial trials, but some was used in specialized work. For instance, Cubmarine, a small submarine, was used primarily for random searching at 300 to 600 feet, and also as a contact identifier in waters too deep for divers. ALVIN and ALUMINAUT, because of their depth capability, were used in the deeper waters—ALUMINAUT searching the flatter areas and ALVIN, with her better maneuverability, searching the rugged canyons and precipitous ocean bottom to the south. The towed devices, USNS MIZAR sensor sled and Westinghouse Ocean Bottom Sidelooking Sonar (OBSS), were used in covering larger areas removing crew fatigue as a limitation.

Lessons Learned. The lessons learned and problems highlighted by this operation are invaluable for future work. Significant is the effective use of high-intensity strobe lights in the pitch-black sea. The first deep inner-space rendezvous was successfully completed by ALVIN and ALUMINAUT on visual contact using their stroboscopic-camera light sources as well as flood lights at a range of 100 to 200 feet at a depth of 2,700 feet. During initial recovery attempts, a flashing high-intensity light sphere was fastened to the parachute. This light was a valuable assist in guiding ALVIN to the weapon.

The only underwater navigation system used with any degree of accuracy was the 3-D tracking system of the USNS MIZAR. This, although primarily designed to track the sensor sled, was used successfully to track ALVIN and ALUMINAUT. The system included a transonder on ALVIN and hydrophones on MIZAR capable of measuring their relative position with accuracies of 180 feet.

This experience revealed that care must be utilized in selecting pingers and transponders for underwater tracking and positioning. Several instances of equipment incompatibility and signal interference were experienced.

Recovery of the weapon with its chute would have been virtually impossible without the Controlled Underwater Recovery Vehicle (CURV) or a remotely controlled equivalent. The danger inherent in working close to hazards like a billowing chute is obvious. ALVIN came dangerously close to entanglement, and CURV finally became entangled.

The dynamic motion and station-keeping ability of a surface vessel are major barriers or hazards to underwater operations. Therefore, until we can get below the surface for long periods of time, we must be able to accurately predict weather conditions and their effects on underwater currents, wave systems, and surface conditions. In this area we can look forward to a weather satellite system and refinement in computer modeling techniques for determining analytical solutions to complex ocan processes.

THE MAN-IN-THE-SEA PROGRAM

The only portion of the DSSP underway prior to the loss of the *Thresher* was the Man-in-the-Sea Program to determine the extent to which man can adapt to the ocean environment. Last October, the third major phase of this program—the Sea Lab II experiment—was completed off La Jolla, California, in 205 feet of water. These experiments involved a bottom habitat (Sea Lab II) that provided an underwater base for three teams of aquanauts. Each team spent 2 weeks at ambient pressure to determine if man can adapt sufficiently to an ocean environment and hyperbaric atmosphere to complete typical tasks. Detailed research programs in human engineering, psychology, and physiology were conducted. Important by-products were information and specimens obtained in biological and physical oceanographic programs. Another important aspect of the investigation was a salvage program in which the aquanauts accomplished useful and strenuous work with new and old salvage techniques.

A new concept referred to as saturated diving is being developed in this program. Saturated diving differs radically from present techniques, which limit the duration of dives and the amount of breathing mixture absorbed by a diver's tissues in order to minimize required decompression time and the incidence of diving sickness.

In the saturated technique, a diver's body fluids and tissues are intentionally saturated with the breathing mixture. In 200 feet of water for example, saturation requires about 24 hours. Once a saturated condition has been reached, a person can work from four to eight hours a day for periods in excess of a month without increasing his required decompression time (33 hours). During this period, the diver must live constantly under the same pressure and the same mixture of gases. He must spend his off-duty hours either in a bottom habitat or in a specially constructed chamber aboard a support ship. In terms of the work he can accomplish, a diver using this technique is the equivalent of 20 to 30 conventional divers; and this superiority increases with depth.

The feasibility and practicability of saturated diving to a depth of 327 feet has been proved

in the Sea Lab experiments, by Jacques-Yves Cousteau's ConShelf experiments in the Red and Mediterranean Seas, and in other pioneering efforts. However, to achieve a capability for operation at 600 to 1,000 feet, much research is needed in many scientific and engineering disciplines along with associated development activities.

The critical requirements for life-support systems designed for use by man in the deep-ocean environment obviously increase with depth. Man need not dive to any great depth before experiencing a degradation in sight, smell, taste, and speech. A quasi-weightless state, coupled with zero visibility, can affect man's "sense" of direction seriously, and even experienced divers can become lost in familiar surroundings. During the Sea Lab II experiments, for example, several aquanauts became disoriented in the small shark cage protecting the entrance to the ocean-bottom habitat.

If useful work is to be done safely and efficiently at great depths, systems and equipment must be provided to restore or compensate for the loss of sight and touch and to enable men to communicate and navigate safely. Man must also be protected from the low temperatures that usually prevail at great depths. He must also have adequate tools, an underwater power source, charts and control boundaries, and an underwater weather-prediction capability. It is significant to note that while the Man-in-the-Sea Program is quite different from the bomb-recovery operation, many of the technical requirements are identical. However, the emphasis on life support in the former is much greater [Coyle, 1966]. The sophisticated aerospace life-support experience could be adapted for deep submergence activities, and use of the results of the basic and applied research of many medical specialities should be mandatory. The rapid adaptation by the medical profession of hyperbaric techniques and research data obtained with marine organisms is a very promising indication of the numerous mutal benefits available to seemingly divergent disciplines.

OFFSHORE OIL, GAS, AND MINING

The increasing offshore activity of the oil and gas industry and the various mining companies in the past 10 years has added to the renewed interest in the oceans. In addition to supporting many specialized research and development programs of their own, these industries have stimulated support for ocean-oriented scientific and engineering programs by many other interests. However, their activities are now moving into deeper water and to greater distances from land. More extensive and more basic scientific and engineering research is becoming necessary. Adaptation of onshore techniques are no longer technically and economically feasible. In the future these industries will derive great benefit from suggesting and participating in joint programs of broad-based research. Undoubtedly the leadership which will come from them will contribute importantly to rapid progress.

While diving operations are an integral part of any offshore petroleum venture, saturated diving techniques are not presently used to any great extent. The oil companies have been forced by the limitations of divers' availability to devise ingenious methods of construction and production to avoid prolonged need for divers. Once saturation diving becomes accepted, more efficient design, fabrication, production, and repair methods will be available.

The feasibility of offshore operations is greatly affected by depth of water, distance from land, available geodetic control points, and the size and depth of the reservoirs below the ocean floor. Developing the capability for drilling in water depths of 3,000 to 5,000 feet should present no insurmountable problems. However, positioning the drill with accuracy over possible reservoirs requires better navigation equipment. Without this improvement, locating possible deposits indicated by survey maps would be costly and time consuming.

Dynamic positioning of drill vessels and remotely controlled well heads, though costly, will be required. Meeting this need is almost within the state-of-the-art.

The most difficult problems facing the oil and gas industry in deep-water operations (600-1,000 feet) are production and well-control. Production is defined as drawing off at the well head, transportation to shore storage, and cleaning of products. Well control is defined as tapping the various strata in sequence and taking advantage of well pressures and liquids to obtain the maximum economical yield per reservoir.

Production requirements in deep water should be subjected to intense research and development, especially the fabrication and maintenance of the draw-off and transportation piping. These members must withstand the high internal pressures and the hydrodynamic battering of the oceans, as well as corrosion and possible cyclic loading caused by turbulent flow. Strong currents in some locations can scour away ocean bottom sands supporting heavy structures. Such scouring action contributed to the tragic collapse of "Sea Gem," a drilling structure, in the North Sea in early 1966.

It's apparent that considerable basic and applied work is necessary on ocean processes and their effects on pipelines and structural members which must survive for long periods of time in a punishing environment. The trend toward stringent water-pollution laws could provide sufficient motivation to avoid failures.

Fluid dynamic modeling coupled with computer simulation of physical systems would result in greater accuracy in designing for complex ocean processes [Krigman, 1966]. A program to instrument full-scale structures now in use for obtaining simultaneous wave and weather data could contribute to a better understanding of random wave systems and provide statistical data for predicting the behavior of the ocean.

OCEAN MINING

Ocean mining activity has been restricted to relatively shallow, "scoop and shovel" type operations for placer deposits of a number of minerals. However, mining in waters deeper than several hundred feet from floating platforms must be carefully studied because of the huge capital investments required and the high cost of ship operation. Therefore, the much-publicized nodules on the ocean floor could conceivably remain as interesting ocean phenomena unless the ocean process can be understood and duplicated by industrial synthesis which could produce artificial nodules in shallow water or enough motivation can be provided for private enterprise to make these operations more attractive economically. A major obstacle to increased offshore exploration for mining is the fuzzy legal rights to discoveries.

RESOURCE ASSESSMENT

By use of examples from the rapidly increasing storehouse of practical deep submergence experience many problem areas have been highlighted in this paper. We have implied that resources are available to effectively solve many of these problems.

If we accept the fact that the need and motivations are present to allow the necessary rapid increase in oceanic knowledge, then a careful assessment of available intellectual and material resources is in order. A cross-fertilization process must be fostered using as catalysts symposia such as this, free information exchange, and wide publication of failures as well as successes to bring diverse interests together for mutual benefit. These diverse interests lie not only within the oceanic community but great proven capabilities are available from other disciplines, from space technology to the humanities.

In the past, advantage has been taken of seemingly unrelated efforts to solve several problems. A few examples are given below to illustrate some of these as well as to show how this interaction of effort can be applied in the future.

- To aid in the solution of the bottom navigation problem, geodesy must provide the geographic mapping of the ocean floor to enable the placement of navigation aids for fine grain search. These aids can be combinations of high-intensity light sources and acoustic transponders already developed by Dr. H. E. Edgerton and others for oceanographic research. A system of temporary and permanent underwater lighthouses and direction finders could be established to permit pinpoint submersible piloting.

- The telemetric guidance of missle technology can be adapted to improve acoustic telemetering techniques thus increasing tracking system accuracy. This would enable searches to be other than random.

- A study and correlation of sensor performance data can lead to improved sensors and enhance the capability to evaluate such data obtained under varied environmental conditions. These data are being collected for oceanographic research and can be made available to the sensor system designer. Ocean and bottom conditions prevailing in future operational areas could then be used to select the proper sensing system, rather than use the "shot-gun" method.

- The USNS MIZAR was designed as a research platform, yet without her capabilities both the *Thresher* search and the Palomares Recovery would have been much more difficult, if not impossible.

- The life-support system in Sea Lab II was adapted directly from our SSN and SSBN systems. Further refinements were required to allow operation in a hyperbaric helium atmosphere.

- Experience in life-support systems presently in use or under development for manned space programs are directly adaptable for future deep-submergence application.

- The physiology required for the Man-in-the Sea effort has given rise to a new form of medical treatment. Hyperbaric medicine is now an accepted method for treating gangrene and emphysemia and for certain types of surgery.

- The design of underwater tools and remote-control devices can benefit from the field of human engineering and the nuclear and space technologies.

- The need for self-contained energy sources for underwater application is well known. The established background in nuclear, isotopic, and various battery-type energy sources reveals that the development of fuel cells and internal-combustion-type converters must be emphasized. Extensive experience is available from torpedoes

and prenuclear submarine machinery research efforts.

- Computer technology and statistical analysis procedures can be adapted to predict complex environmental processes using small data samplings.

CONCLUSION

The magnitude of the technical, economic, and geopolitical problems germane to successful exploitation of the oceans makes it imperative that the resources available are properly assessed and effectively utilized.

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Session VI Panel Discussion

DR. R. A. GEYER, *Chairman* (Head, Department of Oceanography, Texas A & M University, College Station, Texas).

MR. BEACHER (U.S. Naval Applied Science Laboratories): Dr. Nettleton, what geodetic accuracy would you like to have beyond a 100-mile range for oil surveying?

DR. NETTLETON: Well, I do not know whether to call it geodetic accuracy or not, but we want relative accuracy within a net so that if we lay out lines that are supposed to be three miles apart, we know they are—or if they are only two and one-half miles apart, we want to know it. We need contour maps, and we do not want to have to shift these lines around to make the map look right. It is not so much I guess what you would call geodetic accuracy as it is relative accuracy—for most purposes the order of a fraction of a mile. The individual positions along a line, relative to one another, are commonly taken ten minutes apart. These positions should be correct within a 100 feet or a couple of 100 feet, or something of that general order.

DR. GEYER: Are there any other questions from the audience?

MR. MOURAD: When we speak of geodetic requirements and accuracy, it must be remembered that there are many degrees of accuracy.

DR. GEYER: Are there any other questions at the moment? Perhaps we can call on some of the panelists who might like to ask other panelists questions.

DR. WORZEL: I would like to know what a supersaturated diver is?

MR. COYLE: There are supersaturated divers. We do not like to have them supersaturated too much because if they are supersaturated to say in excess of thirty feet of water, of course it varies between individuals, the gases boil out, and they are bent. In some cases they can end up with air—or gas embolisms in this case, because we use helium oxygen, and in some cases nitrogen mixes.

The saturated diving technique which we are employing differs from the conventional diving where you limit the time on the bottom and also limit the amount of gases that are absorbed by the body fluid and tissues, in order to cut down the amount of time required for decompression and also to limit the cases of diving sickness.

In the case of the saturated technique, we intentionally saturate the tissues of the diver, and he is maintained under approximately the same gas pressure and same gas mixtures for long periods of time so that he can be transported down to a work site to a submersible decompression chamber. We could probably get anywhere from four, five, or even eight hours of work from that diver every day. That one diver is equivalent to thirty other divers just working at a depth of two hundred and ten feet. Does that answer your question?

DR. GEYER: I should point out that the person who responded to the question, Mr. Coyle, is coauthor of the previous paper. Commander MacKinnon had to catch an airplane. Do we have any other questions?

MR. RODIN (Air Force Systems Command): Dr. Nettleton, I judged from your comments that there is nothing available now to solve your positioning problems. Do you believe that something new must be found?

DR. NETTLETON: The shore-based location systems of the type we have been using, that is, the medium frequency and ultra-high frequency systems, the Shoran or the Loran radius type, have been quite satisfactory. We are still using those techniques for the detailed exploration we are attempting with seaborne gravity meters to extend offshore the type of work which has been done using bottom meters in the deeper waters. They reach out far enough. We have some trouble with loss of signal, but on the whole they have provided satisfactory location services.

Now, we would like to be able to go to a new area, or to go farther out. There is real interest in extending particular gravity information for commercial purposes much farther out.

These are because of interests in some of the theories of the formation of ocean basins and sedimentary deposits which in the long range are of interest for possible ore deposits.

Now, for an isolated line of that kind, I believe that if we could get satellite navigation systems to the order of a thousand feet or VLF of Omega locations to a similar order, and could have occasional fixes and could maintain a very careful navigation between them, we could get a satisfactory system. But, if we want to carry out a rather close net, which is at all comparable with the kind of nets which have been made by underwater meters, we need something somewhat better than that, as I understand these capabilities to be at this time. Also, it would be a lot nicer if we could go along with a boat, and not have to go there two weeks ahead of time to set up a location system

before we could go to work, and spend a lot of money in getting it set up and doing land surveying and all of the things that are necessary to set up a short-wave system. If we could use these new methods, anywhere we want to go, it would certainly be a great help to carrying out operations in new areas.

MR. FRAZIER; May I speak about that for just a moment? I think it's just a little dangerous to try to generalize on what precision factors, depending on what you want and what you're talking about, that the oil industry might want. It depends on what the industry is doing out there, whether they are conducting reconnaissance surveys or doing detailed shooting. In many cases, they may not be too concerned about location except to know they are on the lease. They're interested in where points are with respect to each other, and to be able to come back to one of the points in case the area turns out to be of interest. As I understand, this isn't always the case. The concern is that if they go farther offshore, beyond the present capability of systems, this problem can only be worse. If the oil industry, I think the oil industry is the best group, will draw up a set of requirements or desires as to the accuracy or precision they need and present them to the geodetic community, I think the geodetic community might make a contribution.

COMMENT FROM FLOOR: I would like to go back to the idea that was generated quite some time ago by Maurice Ewing of putting down bottom beacons. It seems as far as long-term, long-range thinking is concerned, that it is logical to consider an ocean bottom network with presumably full exploration for the next ten, twenty, or fifty years, to explore and to utilize the ocean for not only military purposes, but for commercial and industrial purposes. I would like to ask the panel in general if they think that perhaps a network of underwater transponders, beacons, and landmarks would be the useful technique to accommodate this transportation of the future, which also has been considered as an underwater media.

MR. WHITTEN: I would like to reply to that stating that the economic situation must be considered very carefully. When a geodetic network is extended over the continent, you will note that the surveys are made in the area where economic development is taking place. If resources are being developed in specific areas on the continental shelf or on the slope, I would agree with you, that it would be highly desirable and perhaps economically feasible, to have a system of ocean bottom beacons. It must be related to the economics of the situation.

DR. WORZEL: I was coauthor with Dr. Ewing on that paper you referenced. I would like to say that the beacons which were proposed originally, eight or ten years ago, were tried out quite successfully. In fact, we translated that into a proposal for benchmarks which has been given in similar detail in this conference. It is quite feasible to do this, possible to do it, but this three to five years lifetime of such beacons makes it impractical to use unless you plan to exploit it in that three- to five-year period. Since this has not yet been the case in the ocean, it has not happened. I suspect that as soon as people to intend to exploit the oceans, they will employ the technique. As far as bench marks in the deep ocean are concerned, I would like to comment a little bit about it, because I think it is not understood by the audience perfectly. On land, a bench mark is usually a brass plaque fastened to a piece of rock, and you locate yourself as much as possible directly over it. At sea it is possible to do this, but usually it is economically impractical. You can get back to the same spot as accurately as you want with a network of transponders, such as have been described, but it is impractical; it is usually much more logical to bring your ship into a region close to the bench mark and then make a correction for the small amount that you miss it. It takes a considerable amount of ship time and maneuvering back and forth to establish yourself on this precise spot. You have to start thinking of bench marks as a region in which you will make a small correction to the point of reference, rather than getting exactly back to the point of reference.

MR. MOURAD: The purpose of the bench marks for marine control points is not necessarily to use them for navigation or to relocate yourself. The purpose, number one, is to provide control points for surveys. When you try to map a certain area, such an area of interest for economic, defense, or any other purpose, then you will need to lay out a few of these points to control your mapping. That was number one. A navigational aspect would be secondary. You could go over these points as needed, but to use them for transportation or things of this sort is probably not practical at this time. The important point is that it is a control network on which to base surveys.

QUESTION FROM FLOOR: I would like to address this to Dr. Worzel. You mentioned the time period for your beacons; I do not know if I missed it someplace in the symposium or not, but using the modern techniques, how much longer could you have expected useful life for beacons under present conditions? You said you figured three to five years. How much has that increased today?

DR. WORZEL: Well, this is the figure that was given at the conference here, for the lifetime expectancy of nuclear battery packs. Actually, we have been trying for eight years to get hold of a nuclear battery without success. The more conventional batteries are available, and usually last on the order of one to three years, but five

years is conceivable with a nuclear power-pack, as described in the literature.

COMMENT FROM FLOOR: I would like to make a comment with regard to this benchmark business. When you consider the use that you plan to make of these, if you are going to use them for navigating ships, as people have sometimes proposed, you are faced with a very bad noise problem at the receiving end. In general, these things are easy to use if you are very close to them, or, if you reduce your speed so that you can hear signals at rather low levels. But beyond this, if you were to take an ocean liner right across the ocean, the percent of time that you could hear a beacon that was several miles away probably would be very small; so if you want to think in terms of the signal-to-noise ratio problem you might think about this.

DR. HEISKANEN: I would like to mention the gravity survey made by Prof. Honkasalo over the Baltic Sea and the fact that he obtained quickly and economically accurate positions.

DR. GEYER: Just one more question and then we will have to adjourn this portion of the meeting.

COMMENT FROM FLOOR: I would like to make one remark in this respect; it is something that should be considered at this time. The U.S. Navy has done an extremely good job in Project Magnet, the airborne magnetic program. However, there is, in our opinion, one problem. That is the usability of the data. The data is very nice, very good, and is very usable, except if you want to put it in a computer. The data is recorded on film strips, and there is a very laborious digitizing job that has to be done to put it into a computer. I think, in collecting all kinds of oceanographic data, computer applications should be kept in mind initially. This is the only way that we are able to look at the data. Apparently, there is some effort to make oceanographic data more readily available, in reference to formats, and so on. This is something that should be done.

DR. GEYER: One more question.

CAPT. JONES: I have no question, but I'd like to present the position of the Coast and Geodetic Survey in regard to marine geodesy.

The extension of bottom markers or subsurface buoy markers into the oceans is going to be terrifically expensive. The locations of these markers is going to be dependent upon the existing art of navigational control, electronics, etc. If you start out with a doubtful location, the recovery of putting the ship over this marker and calibrating a navigational system is also doubtful, time consuming, and costly. We think that it might be better to put this money into upgrading electronic systems, shore based; man them continuously, the same as we man our lighthouses; and have an available system for all to use at any time. Now this is also going to be costly and require a lot of resources, but should—could be instigated, initiated in pilot projects such as Louisiana Coast or other areas of great activity. We think that rather than spend a lot of resources in locating marks on the bottom or for buoys whose permanancy is questionable and very costly, that we should be upgrading our electronic, navigational systems to give the geodetic accuracy at great distances.

Remarks by Mrs. Irene Fisher
Army Map Service

MRS. FISHER: I hope I have the permission of this audience to express, in the name of all of us, our thanks and appreciation to the organizers of this symposium. These three days have not only been a stimulating experience, but we have been privileged to witness a historic event in geodesy; a new branch, marine geodesy, is being formed and, we hope, will expand to an inter-disciplinary endeavor, with international cooperation. The resolution we just voted on is the first formal step in this direction.

Our thanks go to the Battelle Memorial Institute and the Coast and Geodetic Survey as sponsors. To Mr. George Mourad, specifically, as the originator; to all and every member of the Program Committee, Cochairmen, Mr. Mourad and Professor Heiskanen, to Battelle Memorial Institute again, for their hospitality, and, of course, last, not least, to all the speakers.

Special Panel Discussion

DR. GEYER: Well, perhaps, as is said for TV programs, the more audience participation the better the program. We might start with suggestions and comments from the floor referred to the panel. You are keeping notes, I understand.

CAPTAIN MOITORET: Well, I have a few notes, if I want to break the ice here, while you are thinking of your own questions. I'll just step right in.

My observation here is that in the last three days we have heard an awful lot of things here that were not geodesy at all. I do not think that is necessarily bad, either. In fact, I think it is rather good, because of the few people here who were brave enough to identify themselves as "I'm a geodesist," rather than "I'm an applied communicator, or old chemist, or oceanographer, or something." There are some geodesists here, and the fact that they got an interleavening with the other kinds of information discussed which are peripheral, gets them out of their cubicles and makes them think broader, too. I think that is fine. But we have not really talked very much about what I thought geodesy was. I do not think, we have already cleared the air, that we want to try to oversell geodesy. Dr. Spiess probably put it, already this afternoon, the right way. Apply the geodesy where geodesy is really needed. If any of you people want to leave this building and drive up to Cleveland, I do not think you are going out and put a gyro in your car, put a star-tracker on the hood, and ask Dr. Whitten "where's the nearest bench mark, first-order control," so you can orient your Esso map and follow Interstate 91, with a stop every five minutes to be sure you have that last decimal place of seconds of longitude. You do not do it that way. In fact, you can get from here to Cleveland without a map at all.

I have made some other notes, though, about what we might do. We can be very good Monday morning quarterbacks on the Program Committee and realize now how we might have made this program better—the gaps, the things we did not hit enough, the things we did not hit at all. It is obvious that we need to publicize the Mercury datum, and make sure that everyone knows that there is such a thing, and that it is going to be completely unclassified as a single, integrated, worldwide geodetic datum, that the Loran C stations will be referred to it, and that we can use Loran C in nearly every place, with coordinates coming out in that datum.

The satellite programs did not get quite enough attention here. Our own national geodetic satellite program was hardly mentioned at all, and it has a great deal that applies over the ocean as well as the land. The use of the Navy navigational satellite system in its use today, was covered by just one speaker, with one ship, the research ship Vega, or Bema, excuse me, but it has been used a great deal more than that already. There is a lot more experience already with this that could have been spoken to, and there is already a commercial firm making receivers, so that pretty soon anybody can have one. We did not get many facts and figures on prices of things like this, either. I understand that the Navy cost of a navigational satellite receiver, the ANSRN-9, is about $50,000. The Navy always pays more for these things than the public generally, does, because we have to have them made to military specifications, and this means build them so tight that they will never fall apart, but I do not know what the commercial price is of these; that $50,000 was only supposed to be the initial prototype price anyway, and they are expecting even the kind that BuShips makes us buy would come down to around $35,000. As to Loran C receiver, I think the going price now for ones we would buy is $35,000, which means the ones you buy are probably cheaper. The Navy has a program going to make this whole system more accurate. We mentioned it will not be accurate—this was brought out by Dr. Newton—until we get the total earth gravity field wrung out better. Then we will get a final, ultimate, finer accuracy out of it. Until we do, the predictions of the next orbit cannot be made exactly accurate yet. The Navy has a program for testing some of the receivers that do exist so far, in ports all around the world, for a total system evaluation of the navigational satellite system. This will contribute further to the accuracy and tying in.

You noticed on the chart of the fixes, which had been obtained with the satellite system, it looked like the center of the circle was not where the ship was. Well, that did not mean the system was wrong; it meant the chart and the system were not on the same set of coordinates. I think everybody probably got that idea. If the chart had been made on a earth-centered set of coordinates, it could have been shifted over and everything would be in agreement. This, again, is a step needed

for the future, to decide on a set of worldwide coordinates, as well as a worldwide datum, so that when you set fixes with this kind of equipment, it will match what is on your charts.

The requirements of oceanographers were not quite completely addressed in this conference. We had a fine representation of oceanographers here. Just exactly how accurate they need to know positions was not resolved. I do not think they really know themselves, yet. Their science is still so, I do not want to say "infantile" because I'll get knocked off my seat, much in its infancy, compared to where it is going, that there are all kinds of requirements still to be defined, as to how well they need to know something, to what fraction of a decimal point.

The classification of data certainly does need attention, and I think it has to have it. I would make a suggestion; speaking only, now as Vic Moitoret, and not as a Department of the Navy representative or Department of Defense representative. I think one answer might be to get a panel of consultants, appointed by the Defense Intelligence Agency, from industry and the academic and scientific community, to sit down and trade some blows on just where can we draw the line that Professor Woollard talks about on what is really going to hold us back more, for if we classify it, we would not have the science and industry people understanding our problem and working with us to contribute to it or if we bury it under the rug behind the Top Secret safe door. So this, I think, could be attacked.

The question of making data available to industry is also something that deserves more attention than it has had here, with just some little pot-shots back and forth and snipping. We are always in the pillory, in the dock for not giving enough data to industry, whether it is bathymetric data, geomagnetic data, and another one this afternoon—Project Magnet of the Navy, which is wonderful, but the information is in the wrong form. We want it for computers. Now, we have a program going to put it all into computerized central library form and store it for automatic handling, but we are not doing it to supply industry. I am sorry, we are doing it because we have to have it that way ourselves to handle it. The tail cannot wag the dog. This Navy does not exist to supply the data to industry. You will hear the argument: "Well, gee; industry pays all these taxes and supports the government. Here the government goes out and collects data, and industry cannot get hold of the data. This is no way to run a railroad." No. That is true; of course there is an element of truth in it. The people that have the data in my office are not being paid to massage data and give such information to industry; it is the U.S. Naval Oceanographic Office, and we exist to support the Fleet, primarily. Now, if in supporting the Fleet, as a by-product we can also make data available to industry, commerce, scientists, fine. But, if we have to wait until next week to do it because the Fleet needs something today, we are always going to do it that way. That is what you would expect us to do, because you want us to have the best Navy in the world, too.

But this has to be solved, and maybe the only way to solve it is to set up some external thing, outside the Department of Defense, where all unclassified data can be in one place where defense needs do not have to come first. We are always going to have to give priority to defense needs in our business and our office. So, we always look like the dog in the manger on this, that we are sitting on the data. That is not our primary mission. It is only when we can get to it, dig out that bathymetry that you want up there at Wood's Hole, dig out the magnetic data that you want in the Gulf Oil Corporation, or what have you, that we can get around to that, if we do not already owe something last week that we are over due on to support Vietnam.

Well, that is all that was on my chest as to where we might go.

DR. GEYER: Thank you, Captain.

MR. WILLIAMS: I would like to change the tone just a bit. I think Captain Moitoret preempted some of my notes. I would like to indicate, with certainly wide-open awakeness on the point, and in the last three days, I feel very confident from the research and development side of geodesy, that the requirements of marine geodesy, as we know them today, and I stress that "as we know them today," can be readily satisfied by existing technology with variations. Of course, the key thing is: How much is it going to cost, and is it going to be worthwhile? But as far as new technologies coming forward, I do not see the real necessity for a magnitude of new Cadillacs to do the types of jobs that we have in front of us right now.

DR. GEYER: Does anyone else on the panel have a comment at this point?

MR. WHITTEN: We have heard about the different disciplines that are present. I want to speak of the different groups that are here, in a different sense.

The first day we had some students introduced to us. I hope that they are still here, that they have seen something of the excitement and challenge that might be ahead of them if they elect to go into a profession in which marine geodesy might be a part of their work. We have university professors here, and we hope that they have seen their responsibilities in guiding and counseling their students.

Now, we have two types of industry represented: the instrument designers and makers, and those

who are using the instruments in mining, petroleum production, and similar activities. Then we have a fourth major group—service agencies of the government. The DOD is a service agency to the people. I would insist that they are a service agency to the people. Getting these user groups from industry and the service organizations of the government together points out certain problems. I see an immediate requirement that is of a geodetic nature. Geodesy is one of those sciences which prides itself on the orderly collection of data, the analysis of data, and the dissemination of data to users. So there is an immediate requirement for the users. A lot of geodetic work is being done on the continental shelf and beyond the shelf. These data need to be collected, they need to be analyzed, they need to be compiled, and they need to be disseminated or made available for dissemination. This is a responsibility, then, of one of these service organizations, to see that this service is given to the users.

That is all I have.

DR. GEYER: Thank you sir.

DR. WORZEL: I would like to say that I agree with Owen Williams, that this conference has brought out the fact that we have the tools that are needed for the geodetic jobs that were pinpointed at this conference. This does not mean to say they will be adequate two years from now, and certainly research must go on in that direction. One thing that I feel strongly about that is likely to cause great difficulty in the near future is this open-ended law of the sea, passed by the United Nations, which makes the definition of the Continental Shelf so indefinite. In fact, there are people, and I have talked to many of them, who plan to use this to mean the Continental Shelf extends halfway across the ocean until we meet the European nations coming across from the other direction. If this is applied in this fashion and, if in fact, there is no time limit on giving permission to do scientific research, we may well see the day when no scientific research can be done. I think that attention needs to be given very seriously to this problem by such a group as this.

DR. GEYER: Very good. Dr. Nettleton.

DR. NETTLETON: Well, I will have to say that, for me, this has been something of an eye opener, in making me acquainted with the possibilities of some of the long-range navigation systems that have possible applications to some of the exploration work which the petroleum industry is doing. These systems are better apparently, than most of us, who are not very closely connected with them, though they were. Iam not quite satisfied in my own mind how available they are at the moment, and how readily the commercial industries can begin to apply them in their routine operations. I hope to learn more about that some day. Maybe Dr. Worzel can comment on that.

DR. VON ARX: In the first go-around, Captain Moitoret said that oceanographers do not know what they want. That hit me right between the eyes, and he also said that we had discussed matters of geodesy, but I think we omitted one very important province of geodesy; namely, we have been discussing mostly the X and Y of geodesy, but neglected the Z, the vertical, the height problem. I believe, as an oceanographer, that this is the most important thing that we are not able to measure at sea. In other words, we cannot trace the level surface across oceans with sufficient accuracy. We do not have the instrumentation for it, so that if we are to do responsible oceanography in the future, it seems to me there is an opportunity for good physics and good engineering to provide us with the means for making such measurements. Here is a first-class challenge.

DR. GEYER: Thank you, Professor Von Arx. Professor Browne?

PROFESSOR BROWNE: Well, I am sure you have all heard a great many technical and interesting points; I think the one thing that I can contribute, perhaps, is that so far as I can see, I am the only foreigner on this panel. I would like just to say how very much I and, I am sure, everyone who is not a citizen of the United States have appreciated your courtesy and kindness in letting us come to this extremely interesting symposium, where I have heard very many interesting things, have met a lot of old friends again, and have personally benefited from it and enjoyed it enormously. I would just say most sincerely to you all—thank you.

DR. GEYER: Thank you, very much, Professor Browne. We are certainly most happy to have you here and contribute so significantly to the success of the conference.

Now, I was noticing, while I was standing here and the panelists were talking, the makeup of the panel in terms of the various major categories of our scientific community; namely, the academic, the government, and industry, and lo and behold, there is only one man from industry on the panel. Here I had a hand in the selection of it. I keep forgetting I am on the other side of the fence now; I am in the academic world. Up to July 1st I was in industry. In order to try and offset this heavily weighted group that we have up here of nonindustry people, I know there are some more industry people in the audience, and perhaps when we, if we could hear from them, if they have anything they would like to say at this time. I know there is a gentleman here from Shell that might be interested in making a comment. Dr. Smith?

DR. SMITH: I really do not have any comments to make, except that I have enjoyed the session very much and learned a lot.

DR. GEYER: Well, we are certainly happy to have you. Dr. Hammer, would you care to say anything from the industry viewpoint?

DR. HAMMER: No. I think that we have gotten a lot of information we came to get. It looks as though there are some useful techniques which we are going to look into and might use.

MR. GRIFFIN: Mr. Chairman, I am an ex-professor of international law who has turned to counseling on the law of the sea from an industry point of view. I came to this Symposium to listen and had resolved not to say anything about the law, but the question has been raised and seems to be a matter of some concern.

I have been in contact with a number of oceanographic industry groups and they, too, seem very much concerned about the legal problems of operations in international waters. But, like Mark Twain's comment about the weather, no one is doing anything about it. The bar associations and the law schools are not doing anything about it because they are not aware of the problem. The State Department is not doing anything about it because apparently it sees no need.

The Marine Resources and Engineering Development Act of 1966 calls for the Marine Resources Council to make a legal study. This will be a government report.

The oceanographic industry and science communities have a common interest in clarifying and promoting freedom of research in the ocean and the legal protection of ocean installations, platforms, and buoys. I believe these two groups should invoke the aid of some scholarly agency, such as the Battelle Institute, to produce a study of these legal problems from the viewpont of industry and science.

I have had another thought while listening to the discussions of charting ocean space: Why not chart legal information regarding offshore areas?

The baseline for the delimitation of all outer offshore boundaries is the low water line. The charting of this line would make it possible to chart such legal information as the territorial sea of the United States and the outer offshore boundaries of the States, which also marks the beginning of the outer Continental Shelf of the United States.

The charting of the lateral boundaries between the offshore territory of the several States would also be useful when the legal criteria are developed for their delimitation. At the present time such criteria exist for only a few of such State boundaries.

Such charted legal information, even on large-scale charts, would not be precise enough to be positive legal evidence of the boundaries shown. However, it would be precise enough to give a useful indication of the legal status of a given approximate area.

Where Do We Go From Here?

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An industrial firm faced with the problem of answering, "Where do we go from here?" would want a survey made showing the following:

1. The past history and projected outlook on consumer demand for the firm's product;
2. a production and marketing cost analysis;
3. the competitive position of the firm's product with that produced by other companies;
4. the probable life of the product before replacement is required;
5. the obsolescence life of the product because of technological or other changes;
6. a current inventory and inventory distribution in terms of consumer market demand; and
7. the profit return in terms of capital investment required for manufacturing and marketing.

To be realistic answering "Where do we go from here in marine geodesy?" we must evaluate marine geodesy as one of several products being produced primarily through support from the Federal Government. Inasmuch as the Federal Government is not operated as a profit-making organization, we must substitute "national defense and security, and national development and welfare" for "profit" as a justification for there being Federal support for marine geodesy. It also must be recognized that Federal support is furnished through two mechanisms: (1) directed "in-house" operations supplemented by outside contracts, and (2) undirected "out-of-house" programs supported on either a contract or grant basis. We, therefore, need to evaluate the objectives of the two modes of operation. Training in geodesy and fundamental research are obvious objectives of the second group where universities are involved. Other aspects which require evaluation are the degree to which there is duplication of effort and the degree of coordination and communication that exists between federally supported groups. A certain amount of redundancy is beneficial since it creates competitive effort, provides a check on results, and usually leads to a better product. However, duplication of effort on certain operations can also be inefficient and a waste of funds and hard-to-get manpower. Cognizance also must be taken of the fact that political considerations can not be ignored. These frequently lead to "pork barrel" federally supported operations which may or may not have other than political justification. Special cognizance must also be taken of the fact that marine geodesy has definite military values, and that the interests of national defense and security must be weighed against those of national development and welfare in deciding the degree to which the classification of certain aspects of marine geodesy is justified. As military classification has been a problem in geodesy ever since the inception of out-of-sight ballistic gunnery, and as the problem in the oceans is compounded by the role of submarines being operated both as war ships beneath the surface and as mobile, submerged ballistic missile platforms, it might be well to review some of the factors involved.

THE CLASSIFICATION PROBLEM

At best, classification of basic knowledge in marine geodesy (the shape of the earth, ephemeris of a satellite, gravity data, the depth of water, magnetic data, the thermal and salinity structure of the water column, and locations of submerged topographic features) can only be justified on a short-term basis during periods of active warfare since no country or government bureau has a corner on scientific imagination, research potential, or research capabilities. As the oceans are international, anyone can collect data in them. Classification of such data cannot contribute to national security for any length of time because the data are obviously available for the taking by anyone. Furthermore, experience has shown that

military secrets seldom can be kept a secret for more than a few years. There is another aspect to this problem in that the historical record shows that the military establishment in general has always been prepared for the next war minus one. It has always taken a crash civilian program to develop the technology required to meet the exigencies of the war actually being fought. Given enough time, defects in any system can be overcome. However, no nation is now so remote from a potential enemy that it can count on either distance or an ocean barrier as being either an effective part of its defense system or as a mechanism to obtain time. The best safeguard for national security is to maintain both a strong industrial and scientific capability, and this calls for not only the support of the scientific community but access to basic information and the use of advanced technological capabilities for general scientific purposes. To restrict information or advanced technological capabilities to scientists working on directed research or undirected research having recognized potential military significance in effect eliminates a large percentage of the nation's scientific community from effective government service. Not that these men would not be working on science, but because they are working at reduced efficiency, repeating or duplicating studies with inferior equipment, and spending effort and hard-to-come-by funds on problems already resolved. Even worse, such a situation can not help but lead to the development of a feeling of antagonism towards defense laboratory groups, whereas there could be a feeling of cooperation.

In the light of the above, it appears fairly certain that the classification of basic knowledge and advanced technological developments in times of peace is more apt to have a long-term detrimental effect on national security and defense than a beneficial effect. This is so because classification can only inhibit the general advancement of science on which future military systems, technology, and tactics depend.

To illustrate the extend that marine geodesy can be affected by military classification, we have only to list those aspects which are now, or have been classified in whole or in part during the past 20-year period.

Geodetic parameters:

Geometric and dynamic form of the earth.
Intercontinental distances.
Geographic positions on a "best" earth centered coordinate system.
Location of land-based control sites for electronic and acoustic positioning systems used to control offshore surveys and scientific studies.
Location of satellite tracking stations.

Navigational and position control:

Precision position control systems required in the deep-ocean area for mapping geophysical and geological parameters, including the topography of the sea floor; the emplacement and recovery of on-bottom and bottom-moored scientific packages for time sequence studies at fixed locations; changes in deep-ocean structure, current, air-sea interaction, etc.; ship location, speed, and course, with adequate precision for corrections to certain measurements, such as gravity, subsurface currents, and differential drift between ships working as teams on single experiments such as seismic refraction studies.

Environmental data:

Velocity structure of water column.
Bathymetry and bottom geology.
Energy exchange between the ocean and atmosphere.
The earth's surface gravity field.

Satellite data:

Geodetic satellite data.
Orbital and ephermeris information on satellites.

Military classification of the above has been justified at different times on the basis of the ICBM (intercontinental ballistic missile) program in which the locations of the launch site and target and the gravity field from the launch site to the target are all important, and on the basis of ASW (antisubmarine warfare) requirements which depend in large measure on knowledge of oceanic environmental factors influencing acoustic transmission. In the USSR and China, and even in certain Western-bloc nations there is total classification of all geodetic and gravitational data even though it must be recognized that in this era of nuclear weapons, and satellite mapping and surveillance systems, such classification has little defense value. Such classification is primarily a political gesture and is no reason for a "tit-for-tat" policy on the part of the United States, particularly when such policy is more apt to be detrimental than beneficial from a long-term military viewpoint for reasons already outlined.

With this background on one of the major obstacles to the development of marine geodesy, let us proceed to consider the analysis proposed.

THE NEED FOR MARINE GEODESY

As brought out in the reports of the National Academy of Sciences Committee on Oceanography, those of the Interagency Committee on Oceanography, the recent Report of the Panel on Oceanog-

raphy of the President's Science Advisory Committee *Effective Use of the Sea*, and Vice-President Humphrey's speech of August 17, 1966, at the first meeting of the National Council on Marine Resources and Engineering Development, the oceans constitute man's last major undeveloped source of minerals and food for an ever expanding world population. Therefore, if we consider only the resources aspect of the oceans, it is evident that they have to be mapped. This is the first step in the economic development of any undeveloped country, and it is the logical first step required before we can start effectively exploiting the full resources of the oceans. Mapping in this case, however, is three dimensional. We not only need to know the geographic locations of the boundary areas and included islands, the geology and topographic relief of the ocean floor, but also the structure of the overlying water mass and its changes with season of the year. Part of such a program can best be done by ships using precision depth recorders, sparkers, or air guns for studying the thickness of sediments, coring devices for securing bottom samples down to depths of 30 meters or more below the bottom, probes for measuring heat flow, bottom photographs, magnetic and gravity recorders for further defining the geology of bottom features, water bottle casts for obtaining water temperature data and water samples for chemical study so the water masses and their nutrient content can be studied. Part can best be done by specially equipped submarines and deep submersibles so that direct observations and sampling can be made of bottom features as well as the flora of the ocean floor and the inhabitants of the overlying water mass. Part can best be done from low flying, slow, airborne platforms using expendable bathythermographs for mapping the thermal structure, infrared sensors and photographic techniques for studying the circulation pattern, and meteorological instruments for studying the energy exchange between the ocean and atmosphere. Part can be done from high-speed aircraft for mapping the gross magnetic and gravitational field and carrying out geodetic mapping missions. Part can be done using moored instrumented buoy systems or on-bottom recording devices so that reliable data can be obtained on variations in various quantities with time.

However, no matter what surveying system is used, a primary consideration in every case is, "Where were the observations made?" Precise position control is, therefore, imperative. On land, positions can be scaled to better than 50 meters from generally available planimetric maps published on a scale of 1 mile to the inch. Comparable accuracy should be the goal for position control in mapping the oceans. This has been possible over much of the continental shelves by installing Decca, Raydist or similar short-range position control systems, but until the recent advent of a satellite navigation system it was not possible in the deep oceans. The existing oceanic Loran net is both limited as to area and range and furthermore, in general, can not give positions consistently that are reliable to even 0.5 mile and more usually are not much better than 1 mile. Operational test of the reliability satellite determined positions indicate that this system can provide a reliable position good to ±0.1 mile. With two receivers the accuracy can be improved to nearer ±0.01 mile. Now that the Mercury Geoid has been declassified, it should be possible to locate measurements at sea with the same precision as achieved on land, and to have both land and sea measurements on the same geodetic system. This is a far cry from conditions 20 years ago when the positions for many islands in the South Pacific were not known to within 15 to 20 miles.

There is thus both a need and a capability for precise position control in the ocean.

Cost Factor. The cost factor, as in many cases, can not be directly evaluated. If the Navy is going to maintain a satellite navigation system for military purposes, and it is to not be classified, the only cost is that of receivers and associated computers on ships and planes. The receivers are currently estimated at about $35,000 per unit, about the same as for Loran equipment. If the satellite navigation system is not to be generally available for civilian use and some other position control system has to be utilized for position control in the oceans beyond the range of Loran, there could still be an improvement in position determination at low cost by utilizing uncompleted VLF Omega system. Certainly the absolute accuracy of positions with the Omega system would not be as good as those possible using the satellite system, but there would be an improvement over Loran positioning, and the relative positioning accuracy appears to be equivalent to that obtainable with the satellite system. The Omega system also offers certain operational advantages over the satellite system in that it is on "every minute" system.

Competitive Aspects. As there is no substitute for position control in mapping, there is no competitive aspect. The competition lies only in the navigation systems available, and as indicated, the satellite navigation system appears to be the system offering the highest precision, with the Omega system offering less absolute precision but other advantages.

Life and Obsolescence. As it will always be desirable to have a bench mark system for referencing positions on a relative basis, any marker system must have an accuracy of the order of 0.1 mile or better to have permanent value. With such

precision there should be no need for repeating control surveys in marine areas. However, it is clear that these will have to be established using a satellite position control system. From the practical standpoint of using marine bench marks or the mapping of natural features in the oceans, 0.1 mile reliability is adequate for all foreseeable purposes. It is only where special situations are involved as in the re-entry of a bottom drill hole that higher precision is needed, and these situations in any case will require a local auxiliary positioning system.

Inventory. The oceans are essentially unmapped, and what mapping has been done is so poorly controlled as to positions that much of it really should be done over again.

The Return on the Investment. As indicated in the Introduction, marine geodesy can contribute and have value for two areas of general concern: national security and national welfare. Both are important and neither can be neglected. There is, therefore, no question about whether marine geodesy should not be pushed in all its aspects. The only question concerns when do we start and the full availability of the capabilities that have been developed. The Coast and Geodetic Survey of ESSA has started a program of bathymetric and other oceanic environmental measurements under Project SEA MAP between Hawaii and the Aleutian Islands. The Bureau of Commercial Fisheries, Hawaii Laboratory, is interested in following up on its pilot study of time sequence measurements at supposedly the same sites in the ocean north of Hawaii. The Naval Oceanographic Office has let three major contracts for studying the acoustic environment in both the Atlantic and Pacific Oceans. Of what value are these programs if positions in large measure aren't good to ±5 miles? How much more valuable would they be if positions could be given with assurance to ±0.1 mile? Will the work that has been done to date not have to be repeated because of poor position control in just a few years because of needs we may not be able to anticipate right now?

CONCLUSION

The answer to the question, "Where do we go from here in Marine Geodesy?" appears to be quite clear. Our first requirement is to make sure the satellite navigation system is generally available and that it is installed on all ships, military and civilian, carrying out mapping programs in the ocean. The second is to make sure everyone adopts the same coordinate system, that defined by the Mercury Geoid. The third is to make sure that there is coordination of effort and joint planning as to what is needed, that priority areas and logical sequences are established, and that funds are obtained for the implementation of a marine geodetic program. As the oceans are so vast, the job of mapping them is going to be difficult enough, as well as so expensive, that duplication of effort can hardly be justified, but neither can the job be assigned to a single agency if there is to be significant progress in understanding and exploiting the oceans.

Fourth, there should be a concentrated effort made to keep both basic geodetic and oceanographic data free of military classification. The military have a definite requirement for classifying weapons systems and associated hardware, but the classification of basic environmental data or procedures for obtaining more precise information on positions which have definite value for the advancement of oceanology can only work to the detriment of national security in the long run.

Fifth, since the oceans are international waters, the legal aspects of exploiting both the ocean floor as well as the overlying waters should be studied. The present Geneva Covenant of 1958 adopted by the United Nations Council in 1964 giving mineral rights to nations "over the adjacent continental shelves and the slopes beyond" is so vague that it can be construed to encompass everything out to the middle of an ocean basin.

Sixth, there is a definite need for more scientific manpower in the field of marine geodesy. Those schools with forward-looking programs in geodesy and with graduate training should be encouraged to expand their field of interest and training to include both satellite geodesy and marine geodesy, and in addition, solid earth geophysics. This last is required if there is to be any significant advance in understanding the factors influencing geodetic measurements. This is true whether we are concerned with ground measurements or satellite data; whether the observations apply to this planet or the maria of the moon.

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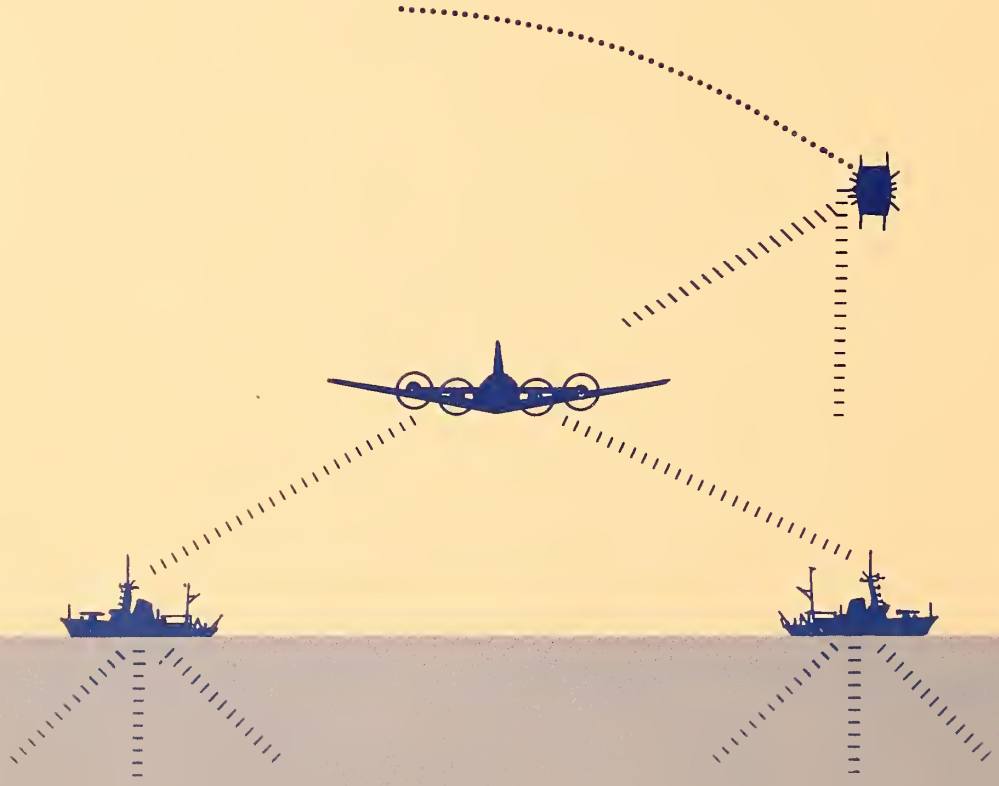

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